

Design of Static Synchronous Series Compensator Based Damping Controller Employing Real Coded Genetic Algorithm

S.C.Swain, A.K.Balirsingh, S. Mahapatra, S. Panda

Abstract—This paper presents a systematic approach for designing Static Synchronous Series Compensator (SSSC) based supplementary damping controllers for damping low frequency oscillations in a single-machine infinite-bus 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. Simulation results are presented and compared with a conventional method of tuning the damping controller parameters to show the effectiveness and robustness of the proposed design approach.

Keywords—Low frequency Oscillations, Phase Compensation Technique, Real Coded Genetic Algorithm, Single-machine Infinite Bus Power System, Static Synchronous Series Compensator.

I. INTRODUCTION

SERIES capacitive compensation was introduced decades ago to cancel a portion of the reactive line impedance and thereby increase the transmittable power. Subsequently, within the FACTS initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the lines and in improving stability [1-3]. The voltage sourced converter based series compensator, called Static Synchronous Series Compensator (SSSC) was proposed by Gyugyi in 1989 [4]. SSSC provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line. The virtual reactance inserted by the injected voltage source influences electric power flow in the transmission lines independent of the magnitude of the line current. The ability of SSSC to operate in capacitive as well as inductive mode makes it very effective in controlling the

power flow the system. Apart from the stable operation of the system with bidirectional power flows, the SSSC has an excellent response time and the transition from positive to negative power flow through zero voltage injection is perfectly smooth and continuous. Also the SSSC could not be tuned with any finite line inductance to have a classical resonance at the fundamental frequency, because the line reactance would, in all practical cases, be greater than and inherently limited by injected compensating voltage produced by SSSC [5-6]. An auxiliary stabilizing signal can also be superimposed on the power flow control function of the SSSC so as to improve power system oscillation stability [7-10].

Several modern heuristic tools have evolved in the last two decades that facilitates solving optimization problems that were previously difficult or impossible to solve. These techniques are finding popularity within research community as design tools and problem solvers because of their versatility and ability to optimize in complex multimodal search spaces applied to non-differentiable objective functions.

In view of the above, the main objectives of the research work presented in this paper are as follows:

1. To present a systematic procedure for designing a SSSC-based controller under small disturbance conditions employing computational intelligence techniques.
2. To compare the performance of modern heuristic based optimization technique and a conventional tuning technique for a SSSC-based controller design.
3. To study the dynamic performance of computational intelligence technique optimized SSSC-based controller and conventionally tuned SSSC based controller when subjected to different disturbances and parameter variations

The remainder of the paper is organized in five major sections. The investigated system is presented in Section II. Power system modeling with the proposed SSSC based supplementary damping controller is presented in Section III. The design problem and the objective function are presented in section III. In Section IV, an overview of RCGA is presented. The results are presented and discussed in Section V. Finally, in Section VI conclusions are given.

II. SYSTEM INVESTIGATED

To design and optimize the SSSC-based damping controller, a single-machine infinite-bus system with SSSC, shown in Fig. 1, is considered at the first instance. The system

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comprises a synchronous generator connected to an infinite bus through a step-up transformer and a SSSC followed by a double circuit transmission line. In Fig. 1 T_1 and T_2 represent the transformers; V_T and V_B are the generator terminal and infinite bus voltage respectively; V_1 , V_2 and V_3 are the bus voltages; V_{DC} and V_{cnv} are the DC voltage source and output voltage of the SSSC converter respectively; I is the line current and P_L is the real power flow in the transmission lines. All the relevant parameters are given in appendix A.

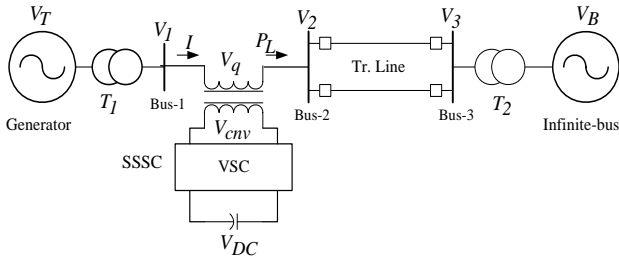


Fig. 1 Single-machine infinite-bus power system with SSSC

III. MODELING THE POWER SYSTEM WITH SSSC

A nonlinear dynamic model of the system is derived neglecting,

1. The resistances of all the components of the system (i.e. transmission lines, generator, transformer and series converter transformer).
2. The transients related with the transmission lines, fixed series capacitor, synchronous generator stator and transformers.

A. The Nonlinear Equations

The nonlinear dynamic model of the system with SSSC [11] is described below:

$$\dot{\omega} = \frac{(P_m - P_e - D\Delta\omega)}{M} \quad (1)$$

$$\dot{\delta} = \omega (\omega - 1) \quad (2)$$

$$\dot{E}_q = \frac{(-E_q + E_{fd})}{T_{do}'} \quad (3)$$

$$\dot{E}_{fd} = \frac{-E_{fd} + K_A (V_{ref} - V_t + V_s)}{T_A} \quad (4)$$

$$\dot{V}_{dc} = \frac{m}{C_{dc}} (I_{t2d} \cos \psi + I_{t2q} \sin \psi) \quad (5)$$

Where,

$$P_e = V_{td} I_{td} + V_{tq} I_{tq}$$

$$E_q = E_q' + (X_d - X_d') I_{td}$$

$$V_t = V_{td} + jV_{tq}$$

$$V_{td} = X_q I_{tq}$$

$$V_{tq} = E_q' - X_d' I_{td}$$

$$I_{td} = I_{t1d} + I_{t2d}$$

$$I_{tq} = I_{t1q} + I_{t2q}$$

$$I_{t1d} = \frac{(X_{Bv} - X_{CF})}{X_{ds}} E_q' - \frac{(X_{Bv} - X_{CF})}{X_{ds}} V_b \cos \delta + \frac{(X_d' + X_{tE})}{X_{ds}} m V_{dc} \cos \psi$$

$$I_{t1q} = \frac{(X_{Bv} - X_{CF})}{X_{qs}} V_b \sin \delta - \frac{(X_q + X_{tE})}{X_{qs}} m V_{dc} \sin \psi ;$$

$$I_{t2d} = \frac{X_{T1}}{X_{ds}} E_q' - \frac{X_{T1}}{X_{ds}} V_b \cos \delta - \frac{X_1}{X_{ds}} m V_{dc} \cos \psi ;$$

$$I_{t2q} = \frac{X_{T1}}{X_{qs}} V_b \sin \delta + \frac{X_3}{X_{qs}} V_{dc} \sin \psi ;$$

$$X_1 = X_d' + X_{tE} + X_T$$

$$X_2 = X_d' + X_{tE} + X_{Bv} - X_{CF}$$

$$X_3 = X_q + X_{tE} + X_T,$$

$$X_4 = X_q + X_{tE} + X_{Bv} - X_{CF},$$

$$X_{ds} = X_1 X_2 - (X_{tE} + X_d')^2$$

$$X_{qs} = X_3 X_4 - (X_q + X_{tE}')^2$$

V_s = The stabilizing signal from PSS.

The simplified IEEE Type-ST1A excitation system is considered in this work. The diagram of the IEEE Type-ST1A excitation system is shown in Fig. 2. The inputs to the excitation system are the terminal voltage V_T and reference voltage V_R . The gain and time constants of the excitation system are represented by K_A and T_A respectively.

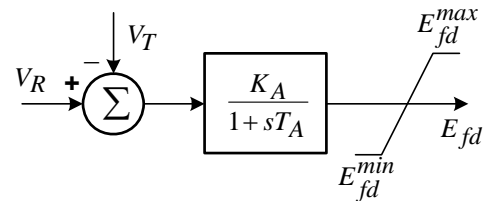


Fig. 2 Simplified IEEE type ST 1A excitation system

B. Linear Dynamic Models

A linear dynamic model (Modified Heffron-Phillips model of a SMIB System including SSSC) is obtained by linearizing the non-linear model around a nominal operating condition. The linearized model is described below:

$$\Delta \dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta \omega)}{M} \quad (6)$$

$$\Delta \dot{\delta} = \omega_e \Delta \omega \quad (7)$$

$$\Delta \dot{E}'_q = \frac{(-\Delta E_q + \Delta E_{fd})}{T_{do}} \quad (8)$$

$$\Delta \dot{E}'_{fd} = \frac{-\Delta E_{fd} + K_A(\Delta V_{ref} - \Delta V_t + V_s)}{T_A} \quad (9)$$

$$\Delta \dot{V}_{dc} = K_7 \Delta \delta + K_8 \Delta E'_q + K_9 \Delta V_{dc} + K_{cm} \Delta m_E + K_{c\delta m} \Delta \psi + K_{cb} \Delta m_B \Delta \psi \quad (10)$$

Where,

$$\Delta P_e = K_1 \Delta \delta + K_2 \Delta E'_q + K_{pm} \Delta m + K_{p\delta m} \Delta \psi + K_{pb} \Delta m_B + K_{pd} \Delta V_{dc}$$

$$\Delta E_q = K_3 \Delta E'_q + K_4 \Delta \delta + K_{qm} \Delta m + K_{q\delta m} \Delta \psi + K_{qd} \Delta V_{dc}$$

$$\Delta V_t = K_5 \Delta \delta + K_6 \Delta E'_q + K_{vm} \Delta m + K_{v\delta e} \Delta \delta_E + K_{vdm} \Delta \psi + K_{vd} \Delta V_{dc}$$

The K_{pu} , K_{qu} , K_{vu} and K_{cu} are row vectors defined as:

$$K_{pu} = [K_{pm} \quad K_{p\delta m}] \quad (11)$$

$$K_{qu} = [K_{qm} \quad K_{q\delta m}] \quad (12)$$

$$K_{vu} = [K_{vm} \quad K_{v\delta m}] \quad (13)$$

$$K_{cu} = [K_{cm} \quad K_{c\delta m}] \quad (14)$$

The vector \mathbf{u} is defined as:

$$\mathbf{u} = [\Delta m \quad \Delta \psi]^T \quad (15)$$

Δm = Deviation in modulation index of series converter. Magnitude of the series injection voltage can be modulated, by modulating m .

$\Delta \psi$ = deviation in the phase angle of series injected voltage \overline{V}_q .

The voltage on the dc link can be regulated, by modulating ψ .

ΔP_m = Deviation in mechanical power input to the generator.

ΔV_{ref} = Deviation in AVR reference voltage.

The constants of the model are functions of the system parameters and operating condition. The modified Phillips-Heffron model of the single-machine infinite-bus (SMIB) power system with SSSC is obtained using linearized equations (6)-(15). The corresponding block diagram model is shown in Fig. 3.

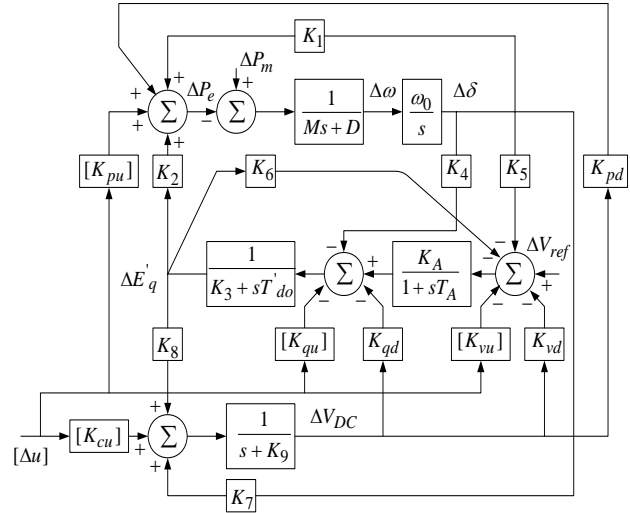


Fig. 3 Modified Linear Dynamic Phillips-Heffron Model of SMIB with SSSC

C. SSSC Based damping Controller

The commonly used lead-lag structure is chosen in this study as a SSSC-based controller. The structure of the SSSC controller is shown in Fig. 4. It consists of a gain block with gain K_T , a signal washout block and two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter, with the time constant T_{WT} , high enough to allow signals associated with oscillations in input signal to pass unchanged. Without it steady changes in input would modify the output. From the viewpoint of the washout function, the value of T_{WT} is not critical and may be in the range of 1 to 20 seconds [12]. In this structure, the washout time constants T_{WT} is usually prespecified [7-10, 13-15]. In the present study, $T_{WT} = 10$ s is used. The controller gain K_T and the time constants T_1 , T_2 , T_3 and T_4 are to be determined.

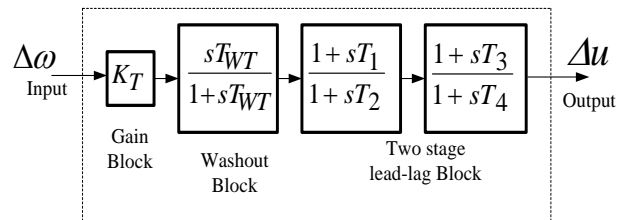


Fig. 4 Structure of the SSSC-based damping controller

D. Objective Function

It is worth mentioning that the SSSC-based controller is designed to minimize the power system oscillations after a disturbance so as to improve the stability. These oscillations are reflected in the deviation in the generator rotor speed ($\Delta\omega$). In the present study, an integral time absolute error of the speed deviations is taken as the objective function J , expressed as:

$$J = \int_{t=0}^{t=t_1} |\Delta\omega| \cdot t \cdot dt \quad (16)$$

In the above equations, $|\Delta\omega|$ is the absolute value of the speed deviation and t_1 is the time range of the simulation. With the variation of K_T , T_1 , T_2 , T_3 and T_4 , the SSSC-based controller parameters, J will also be changed. 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.

Tuning a controller parameter can be viewed as an optimization problem in multi-modal space as many settings of the controller could be yielding good performance. Traditional method of tuning doesn't guarantee optimal parameters and in most cases the tuned parameters need improvement through trial and error. In modern heuristic optimization technique based methods, the tuning process is associated with an optimality concept through the defined objective function and the time domain simulation. Hence these methods yield optimal parameters and the methods are almost free from the curse of local optimality. In modern heuristic optimization techniques, the designer has the freedom to explicitly specify the required performance objectives in terms of time domain bounds on the closed loop responses. In view of the above, in the present study, modern heuristic optimization techniques are employed to solve this optimization problem and search for optimal SSSC Controller parameters.

IV. APPLICATION AND COMPARISON OF TUNING METHODS

A. Phase Compensation Technique

The phase compensation technique is based on the objective of tuning the SSSC based parameters to fully compensate for the phase lag introduced through the exciter and generator characteristics such that the torque changes provided by the SSSC are in phase with the rotor speed deviations.

The following step-by-step procedure is used [12, 16]:

$$\text{Let } \frac{\Delta T_{PSS}}{\Delta u} = GEP(s) G(s) \quad (17)$$

Where,

$G(s)$ represents the transfer function of SSSC based controller.

$$GEP(s) = \frac{K_2 K_A K_3}{K_A K_3 K_6 + (1 + sT_{do} K_3) (1 + sT_A)} \quad (18)$$

Step-1

Neglecting the damping D , obtain the undamped natural frequency ω_n in rad/s

The characteristic equation of the mechanical loop may be written as:

$$\frac{2H}{\omega_s} s^2 + K_1 = 0 \quad (19)$$

The roots of the equations are:

$$s_1, s_2 = \pm j \omega_n = \pm j \sqrt{\frac{K_1 \omega_s}{2H}} \quad (20)$$

Step-2

$$\text{Find the phase lag of } GEP(s) \text{ at } s = j \omega_n \quad (21)$$

Step-3

Adjust the phase lead of $G(s)$ such that

$$\angle G(s) |_{s=j\omega_n} + \angle GEP(s) |_{s=j\omega_n} = 0 \quad (22)$$

$$\text{Let } G(s) = K_{PSS} \left(\frac{1 + sT_1}{1 + sT_2} \right)^k \quad (23)$$

ignoring the washout filter whose net phase contribution is approximately zero. $k = 1$ or 2 with $T_1 > T_2$. Thus if $k = 1$;

$$\angle 1 + j\omega_n T_1 = \angle 1 + j\omega_n T_2 - \angle GEP(j\omega_n) \quad (24)$$

Knowing ω_n and $\angle GEP(j\omega_n)$, T_1 can be selected. T_2 can be chosen as some value between 0.02 to 0.15 s.

Step-4

The characteristic equation is given by:

$$s^2 + 2\xi \omega_n s + \omega_n^2 = 0 \quad (25)$$

where ξ is the damping ratio. (A reasonable choice of ξ is between 0.1 and 0.3)

So,

$$2\xi \omega_n M = K_T | GEP(j\omega_n) | | G_1(j\omega_n) \quad (26)$$

Knowing ω_n and desired ξ , K_T can be found.

From the above technique the single stage SSSC based controller parameters are found to be:

$$K_T = 54.08, T_1 = 0.1631, T_2 = 0.1594$$

B. Real Coded genetic Algorithm

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 [17]. 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.

1. Chromosome representation

Chromosome representation scheme determines how the problem is structured in the GA. 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.

2. 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:

$$P_i = q^i (1 - q)^{r-1} \quad (27)$$

$$q^i = \frac{q}{1 - (1 - q)^P} \quad (28)$$

where,

q = probability of selecting the best individual

r = rank of the individual (with best equals 1)

P = population size

3. 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:

$$x_i' = \begin{cases} x_i, & \text{if } i < r \\ y_i & \text{otherwise} \end{cases} \quad (29)$$

$$y_i' = \begin{cases} y_i, & \text{if } i < r \\ x_i & \text{otherwise} \end{cases} \quad (30)$$

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

$$\bar{X}' = r\bar{X} + (1 - r)\bar{Y} \quad (31)$$

$$\bar{Y}' = r\bar{Y} + (1 - r)\bar{X} \quad (32)$$

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

$$x_i' = \begin{cases} x_i + (b_i - x_i) f(G) & \text{if } r_1 < 0.5, \\ x_i + (x_i - a_i) f(G) & \text{if } r_1 \geq 0.5, \\ x_i, & \text{otherwise} \end{cases} \quad (33)$$

where,

$$f(G) = (r_2 (1 - \frac{G}{G_{\max}}))^b \quad (34)$$

r_1, r_2 = uniform random nos. between 0 to 1.

G = current generation.

G_{\max} = maximum no. of generations.

b = shape parameter.

4. 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 real-coded genetic algorithm optimization process employed in the present study is given in Fig. 5.

Implementation of RCGA requires the determination of six fundamental issues: chromosome representation, selection function, the genetic operators, initialization, termination and evaluation function. Various types of representations of an individual or chromosome are: binary digits, floating point numbers, integers, real values, matrices, etc. Similarly, there

are several schemes for the selection process: roulette wheel selection and its extensions, scaling techniques, tournament, normal geometric, elitist models and ranking methods. There are two basic types of genetic operators; crossover and mutation. Crossover takes two individuals and produces two new individuals while mutation alters one individual to produce a single new solution. The following genetic operators are usually employed: uniform mutation, non-uniform mutation, multi-non-uniform mutation, boundary mutation and simple crossover, arithmetic crossover and heuristic crossover. For the implementation of GA, normal geometric selection, arithmetic crossover and non uniform mutation are employed in the present study. Also, random initialization and specified generations are used for initialization and termination process. Normal geometric selection is a ranking selection function based on the normalized geometric distribution is employed in the present study. 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. A matrix of options where the first column represents the number of that crossover and mutation operations performed in the present study are given in Table I.

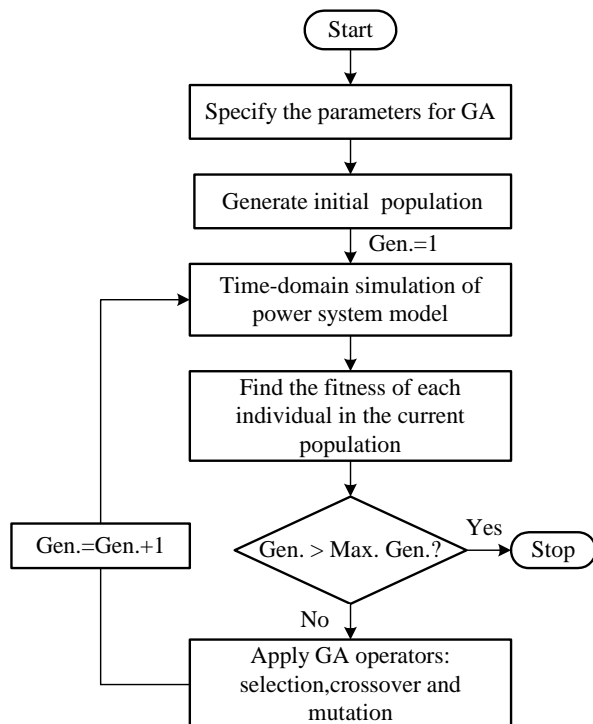


Fig. 5 Flowchart of GA optimization process to optimally tune the controller parameters

TABLE I
PARAMETERS USED IN RCGA

| Parameter | Value/Type |
|---------------------|---------------------------|
| Maximum generations | 100 |
| Population size | 50 |
| Type of selection | Normal geometric [0 0.08] |
| Type of crossover | Arithmetic [2] |
| Type of mutation | Nonuniform [2 100 3] |
| Termination method | Maximum generation |

TABLE II
SSSC BASED CONTROLLER PARAMETERS IN 20 RUNS

| Parameters/ Solution | K_T | T_1 | T_2 | T_3 | T_4 |
|-------------------------|---------|--------|--------|--------|--------|
| 1 | 75.8200 | 0.2787 | 0.3416 | 0.4168 | 0.3229 |
| 2 | 65.7484 | 0.1991 | 0.3658 | 0.4831 | 0.2185 |
| 3 | 83.6769 | 0.1442 | 0.4298 | 0.4766 | 0.1772 |
| 4 | 87.0707 | 0.4363 | 0.2402 | 0.2009 | 0.4062 |
| 5 | 85.7154 | 0.2476 | 0.3468 | 0.4876 | 0.3680 |
| 6 | 78.0890 | 0.4553 | 0.2617 | 0.1841 | 0.3405 |
| 7 | 80.9234 | 0.3192 | 0.2702 | 0.3496 | 0.3971 |
| 8 | 88.5404 | 0.2609 | 0.3485 | 0.4310 | 0.3432 |
| 9 | 67.0650 | 0.1561 | 0.2054 | 0.4527 | 0.3435 |
| 10 | 86.3079 | 0.4042 | 0.3742 | 0.2264 | 0.2565 |
| 11 | 86.8742 | 0.3450 | 0.3289 | 0.1338 | 0.1578 |
| 12 | 87.2629 | 0.3879 | 0.4607 | 0.3043 | 0.2444 |
| 13 | 77.4925 | 0.4498 | 0.2526 | 0.1086 | 0.2417 |
| 14 | 79.3984 | 0.1291 | 0.1485 | 0.3202 | 0.2730 |
| 15 | 88.4906 | 0.1651 | 0.2362 | 0.3126 | 0.2568 |
| 16 | 86.6889 | 0.3630 | 0.1456 | 0.1286 | 0.3547 |
| 17 | 89.7036 | 0.3114 | 0.1667 | 0.1093 | 0.2625 |
| 18 | 82.0820 | 0.4337 | 0.3419 | 0.2585 | 0.3328 |
| 19 | 89.6222 | 0.4087 | 0.3234 | 0.1822 | 0.2574 |
| 20 | 74.1568 | 0.1299 | 0.1981 | 0.4713 | 0.3528 |
| 1 | 75.8200 | 0.2787 | 0.3416 | 0.4168 | 0.3229 |
| 2 | 65.7484 | 0.1991 | 0.3658 | 0.4831 | 0.2185 |

The objective function comes from time domain simulation of power system model shown in Fig. 2.3. Using each set of controllers' parameters the time domain simulation is performed and the fitness value is determined. The objective function is evaluated by simulating the system dynamic model considering a 10% step increase in mechanical power input (P_m) at $t = 1.0$ s. The objective function J attains a finite value since the deviation in rotor speed is regulated to zero. The best SSSC based controller parameters among the 20 runs of RCGA is found to be:

$$K_T = 89.6222, T_1=0.4087, T_2=0.3234, T_3=0.1822, T_4=0.2574$$

V. SIMULATION RESULTS

To evaluate the capability of the Phase Compensation Technique (PCT) optimized SSSC-based controllers and

RCGA optimized SSSC-based controllers on damping electromechanical oscillations of the example electric power system, simulations are carried out. To assess the effectiveness and robustness of the controllers, different disturbances and parameters variations are considered. In order to verify and compare the effectiveness of the optimized controllers, the performance of the both controller are tested for a disturbance in mechanical power input. A 10% step increase in mechanical power input at $t=1.0$ s is considered. The system responses for the above contingency are shown in Figs. 6-8. In these Figs., the responses without control, response with proposed phase compensation technique tuned SSSC controller and proposed RCGA optimized SSSC controller are shown with legends WC, PCT and RCGA respectively. It can be observed from Figs. 6-87 that, without control the system is unstable and both PCT and GCGA tuned SSSC based controller maintains stability. However, the responses with RCGA optimized SSSC based controller are much faster, with less overshoot and settling time compared to PCT tuned SSSC based controller.

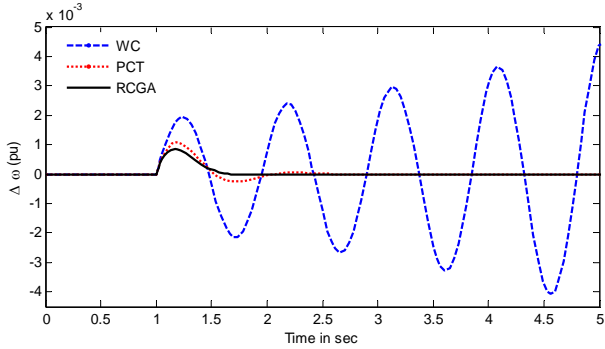


Fig. 5 Speed deviation response for 10% step increase in P_m

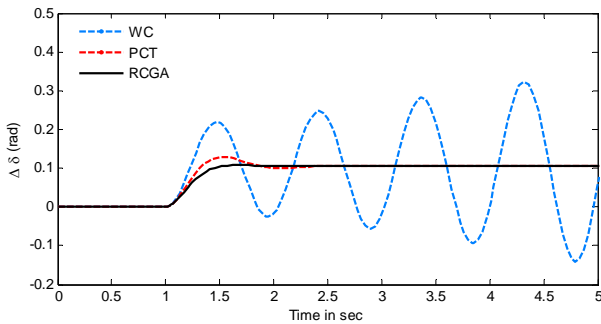


Fig. 6 Power angle deviation response for 10% step increase in P_m

For completeness, the effectiveness of the proposed controllers is also tested for a disturbance in reference voltage setting. The reference voltage is increased by a step of 5% at $t=1$ s. Figs. 8-10 show the system responses for the above contingency for all the three cases. These positive results of the proposed RCGA optimized SSSC based controller can be attributed to its faster response with less overshoot compared to that of PCT.

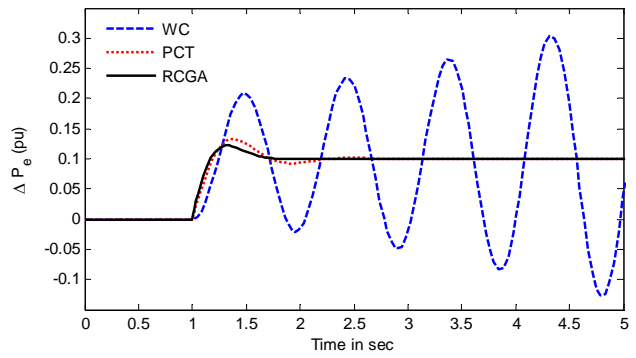


Fig. 7 Electrical power deviation response for 10% step increase in P_m

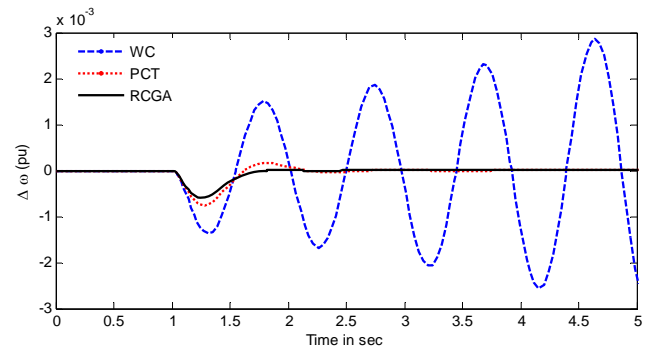


Fig. 8 Speed deviation response for 10% step increase in V_{ref}

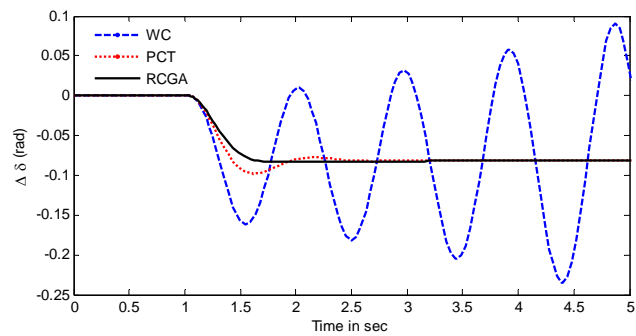


Fig. 9 Power angle deviation response for 10% step increase in V_{ref}

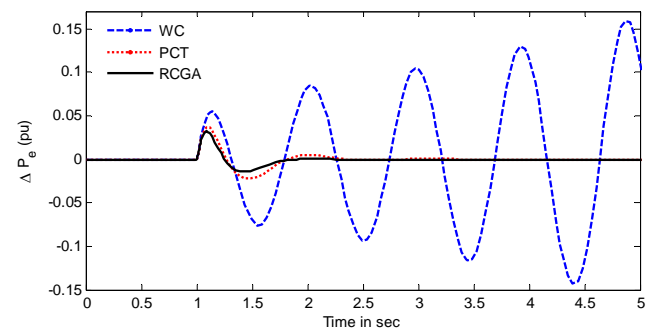


Fig.10 Electrical power deviation response for 10% step increase in reference voltage V_{ref}

In the design of damping controllers for any power system, it is extremely important to investigate the effect of variation of system parameters on the dynamic performance of the system. In order to examine the robustness of the damping controllers to variation in system parameters, a 25% decrease in machine inertia constant and 30% decrease of open circuit direct axis transient time constant is considered. The system response with the above parameter variations for a 5% step increase in mechanical power is shown in Figs. 11-16. It can be seen from Figs. 11-16 that RCGA optimized SSSC controller has good damping characteristics to low frequency oscillations and stabilize the system much faster.

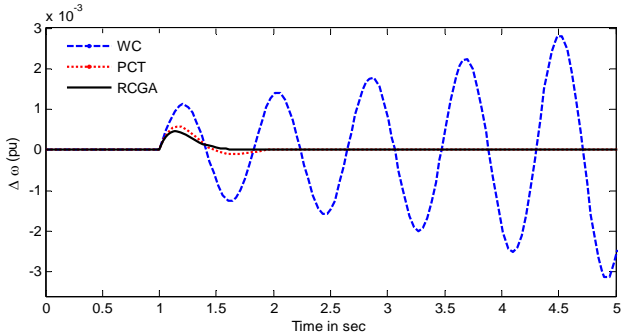


Fig. 11 Speed deviation response for 5% step increase in P_m with 25% decrease in M

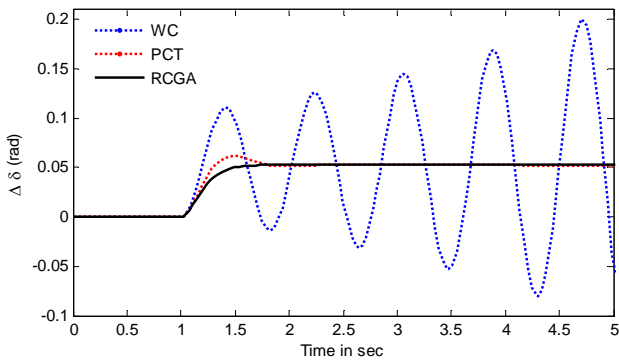


Fig. 12 Power angle deviation response for 5% step increase in P_m with 25% decrease in M

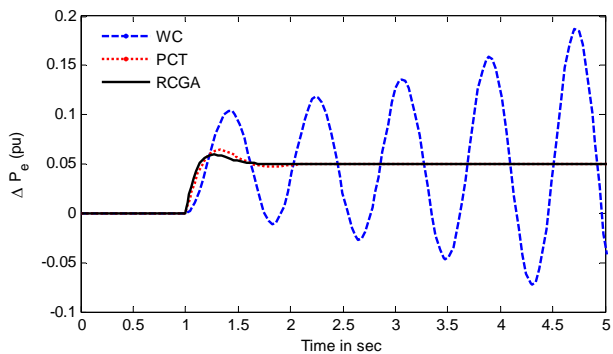


Fig. 13 Power angle deviation response for 5% step increase in P_m with 25% decrease in M

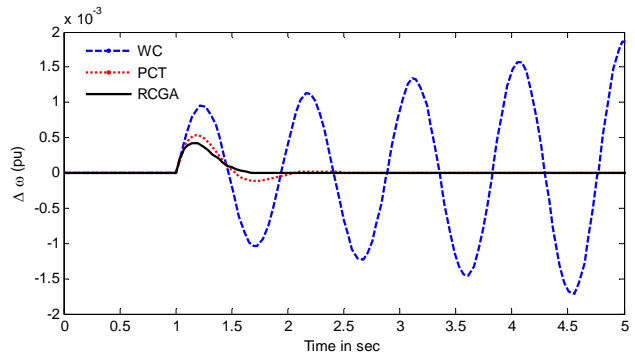


Fig. 14 Speed deviation response for 5% step increase in P_m with 30% decrease in T_{do}'

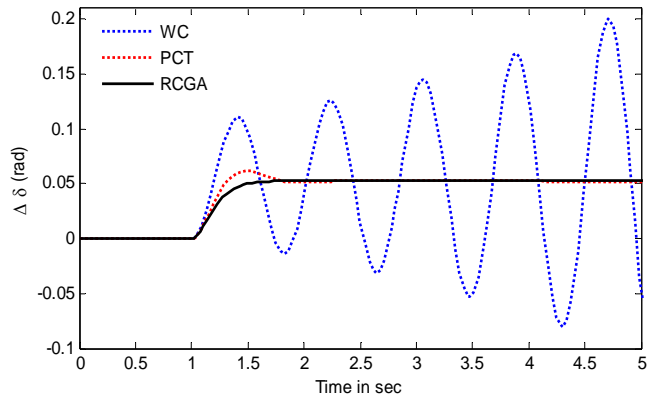


Fig. 15 Power angle deviation response for 5% step increase in P_m with 30% decrease in T_{do}'

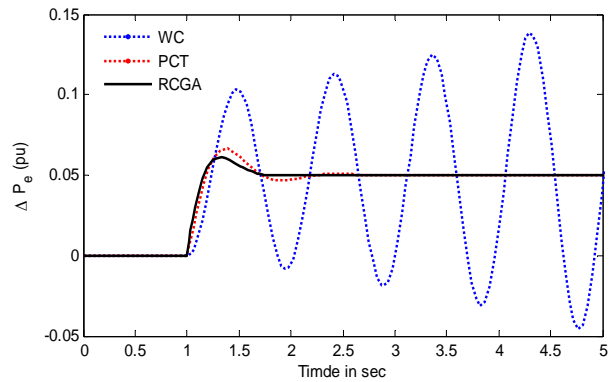


Fig. 16 Power angle deviation response for 5% step increase in P_m with 30% decrease in T_{do}'

VI. CONCLUSIONS

In this study, a real-coded genetic algorithm optimization technique is employed for the design of SSSC-based damping controllers. The design problem is transferred into an optimization problem and RCGA is employed to search for the optimal SSSC-based controller parameters. The performance of proposed controller has been investigated under various disturbances and parameter variations. Simulation results are presented and compared with a conventional phase

compensation technique for tuning the damping controller parameters to show the superiority of the proposed design approach. Investigations reveal that the proposed controllers are robust and perform satisfactorily under various disturbances with parameter variations.

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