

## REAL-CODED GENETIC ALGORITHM FOR ROBUST COORDINATED DESIGN OF EXCITATION AND SSSC-BASED CONTROLLER

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**Abstract:** *Power system stability enhancement via robust coordinated design of a power system stabilizer (PSS) and a static synchronous series compensator (SSSC)-based controller is thoroughly investigated in this paper. The coordination among the proposed damping stabilizers and the SSSC internal injected voltage regulator and dc voltage regulator has also taken into consideration. The coordinated design problem is formulated as an optimization problem with a time-domain simulation-based objective function and real-coded genetic algorithm (RCGA) is employed to search for optimal controller parameters. The proposed stabilizers are tested on a weakly connected power system with different disturbances. Simulation results are presented to show the effectiveness and robustness of the proposed control schemes over a wide range of loading condition and disturbances. The proposed design approach is found to be robust and improves stability effectively even under small disturbance and unbalanced fault conditions.*

**Key words:** *Static synchronous series compensator, power system stabilizer, power system stability, real-coded genetic algorithm.*

### 1. 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 power system oscillations. However, during some operating conditions, this device may not produce adequate damping, and other effective alternatives are needed in addition to PSS [2]. Recent development of power electronics introduces the use of Flexible ac transmission system (FACTS) controllers in power systems. FACTS controllers are

capable of controlling the network condition in a very fast manner and this unique feature of FACTS can be exploited to improve the stability of a power system [3].

Static Synchronous Series Compensator (SSSC) is member of FACTS family that is connected in series in the transmission lines. With the capability to change its reactance characteristic from capacitive to inductive, the SSSC is very effective in controlling power flow in power systems [4]. 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 [5, 6]. The interaction among PSSs and SSSC-based controller may enhance or degrade the damping of certain modes of rotor's oscillating modes. To improve overall system performance, many researches were made on the coordination between PSSs and FACTS power oscillation damping controllers [7-10].

The problem of PSS and FACTS controllers parameter tuning is a complex exercise as uncoordinated local control of FACTS devices and PSS may cause destabilizing interactions. 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 optimisation and also the modern control theory. 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 [6, 11]. Also, most of proposals presented for coordinated design of PSS and FACTS-based controller are based on single phase models and the design is carried out using small disturbances. However, the controllers which are

designed at small disturbance condition may not provide satisfactory results during large disturbance periods. Also, the controllers should provide some degree of robustness to the variations in loading conditions, and configurations as the machine parameters change with operating conditions.

This paper addresses the robust coordinated design of a PSS and a SSSC-based controller employing real-coded genetic algorithm optimization technique. The coordination among the proposed damping stabilizers and the SSSC internal injected voltage regulator and dc voltage regulator has also been taken into consideration.

## 2. System model

### 2.1 Single-machine infinite bus power system

To coordinately design the SSSC-based damping controller and the PSS, a single-machine infinite-bus power system shown in figure 1, is considered. The system comprises a synchronous generator connected to an infinite-bus through a step-up transformer and a SSSC followed by a double circuit transmission line. The generator is equipped with Hydraulic turbine and governor (HTG), excitation system and a power system stabilizer. The HTG represents a nonlinear hydraulic turbine model, a PID governor system, and a servomotor. The excitation system consists of a voltage regulator and DC exciter, without the exciter's saturation function [12]. In figure 1,  $T$  represent the transformers;  $V_T$  and  $V_B$  are the generator terminal and infinite bus voltage respectively;  $V_1$  and  $V_2$  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;  $P_L$  and  $P_{L1}$  are the total real power flow in the transmission lines and that in one line respectively.

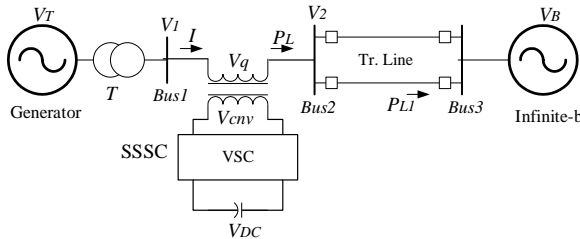


Fig. 1. Single-machine infinite-bus power system with SSSC

### 2.2 Static synchronous series compensator

A SSSC is a solid-state voltage sourced converter (VSC), which generates a controllable AC voltage source, and connected in series to power transmission lines in a power system. The injected voltage ( $V_q$ ) is in quadrature with the line current  $I$ , and emulates an inductive or a capacitive reactance so as to influence the power flow in the transmission lines. The compensation level can be controlled dynamically by changing the magnitude and polarity of  $V_q$  and the device can be operated both in capacitive and inductive mode [3, 4].

The variation of injected voltage is performed by means of voltage sourced converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (e.g. GTOs, IGBTs or IGCTs) to synthesize a voltage  $V_{cnv}$  from a DC voltage source. A capacitor connected on the DC side of the VSC acts as a DC voltage source. A small active power is drawn from the line to keep the capacitor charged and to provide transformer and VSC losses, so that the injected voltage is practically 90 degrees out of phase with current  $I$ .

Two types of technologies can be used for the VSC [12]:

- VSC using GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of voltage  $V_{cnv}$  is proportional to the voltage  $V_{DC}$ . Therefore  $V_{DC}$  has to be varied for controlling the injected voltage.
- VSC using IGBT-based pulse-width-modulation (PWM) inverters. This type of inverter uses PWM technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a fixed DC voltage  $V_{DC}$ . Voltage  $V_{cnv}$  is varied by changing the modulation index of the PWM modulator.

VSC using IGBT-based PWM inverters is used in the present study. However, as details of the inverter and harmonics are not represented in power system stability studies, the same model can be used to represent a GTO-based model.

## 3. The proposed approach

### 3.1 Structure of the proposed controllers

The structures of the PSS and SSSC controller are shown in figures 2 and 3 respectively. Each structure consists of: a gain block; 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 a time constant which is 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 washout time constant is not critical and may be in the range of 1 to 20 seconds [1]. The input to both the controllers is the speed deviation signal and outputs are the injected voltage and stabilizing signals for SSSC and PSS respectively.

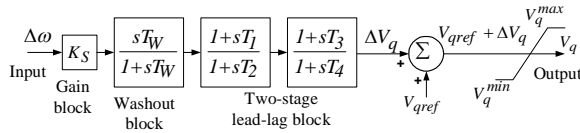


Fig. 2. Structure of SSSC-based controller

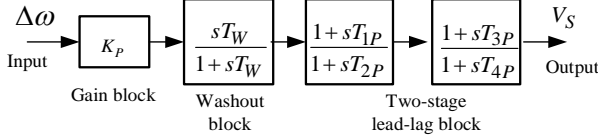


Fig. 3. Structure of PSS

In these structures, the washout time constants  $T_W$  and the denominator time constants  $T_2$ ,  $T_4$ ,  $T_{2P}$  and  $T_{4P}$  are usually prespecified [6, 11, 13]. The gains  $K_S$  and  $K_P$  and the time constants  $T_1$ ,  $T_3$ ,  $T_{1P}$  and  $T_{3P}$  are to be determined. For the internal ac and dc voltage controllers of the SSSC, the PI structures are used. The internal controllers consist of injected voltage regulator and dc voltage regulator. The parameters of these controllers are:  $KP_{VAC}$ ,  $KI_{VAC}$  for injected voltage regulator and  $KP_{VDC}$ ,  $KI_{VDC}$  for dc voltage regulator. These controllers are designed in coordination with the SSSC-based controller and PSS.

### 3.2 Optimization problem

It is worth mentioning that the PSS and SSSC-based controllers are designed to minimize the power system oscillations after a large disturbance so as to improve the power system stability. In the present study, an integral time absolute error of the speed deviations is taken as the objective function. The objective function is expressed as:

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

Where,  $\Delta\omega$  is the speed deviation and  $t_{sim}$  is the time range of the simulation.

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.

## 4. 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 [14].

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.

### 4.1 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.

### 4.2 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:

$$P_i = q \cdot (1 - q)^{r-1} \quad (2)$$

$$q = \frac{q}{1 - (1 - q)^P} \quad (3)$$

where,

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

### 4.3 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:

$$x'_i = \begin{cases} x_i, & \text{if } i < r \\ y_i & \text{otherwise} \end{cases} \quad (4)$$

$$y'_i = \begin{cases} y_i, & \text{if } i < r \\ x_i & \text{otherwise} \end{cases} \quad (5)$$

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

$$\bar{X}' = r \bar{X} + (1-r) \bar{Y} \quad (6)$$

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

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

$$x'_i = \begin{cases} x_i + (b_i - x_i) f(G) & \text{if } r_1 < 0.5, \\ x_i + (x_i + a_i) f(G) & \text{if } r_1 \geq 0.5, \\ x_i, & \text{otherwise} \end{cases} \quad (8)$$

where,

$$f(G) = (r_2 (1 - \frac{G}{G_{\max}}))^b \quad (9)$$

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

$G =$  current generation.

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

$b =$  shape parameter.

#### 4.4 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 figure 4.

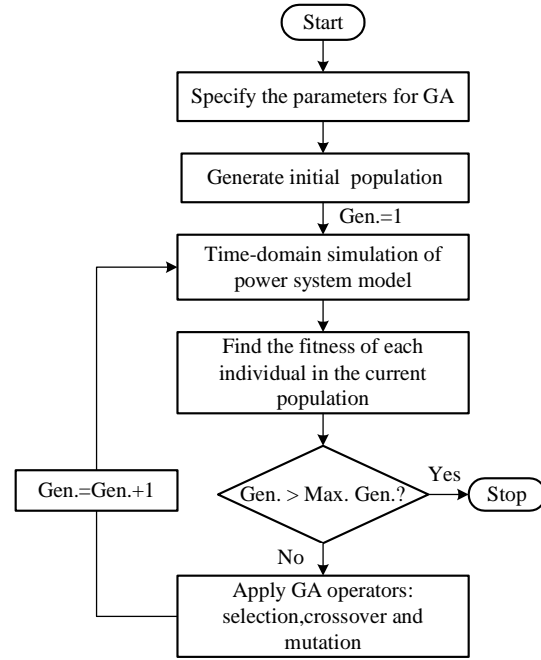


Fig. 4. Flowchart of genetic algorithm

## 5. Results and discussions

### 5.1 Application of genetic algorithm

In order to optimally tune the parameters of the proposed controllers, as well as to assess their performance and robustness under wide range of operating conditions with various fault disturbances and fault clearing sequences, the model of the example power system shown in figure 1, is developed using SimPowerSystems 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 relevant parameters are given in appendix.

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 RCGA 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. Optimization was

performed with the total number of generations set to 100. Optimization process is repeated 20 times and the best final solution obtained are given below.

For SSSC-based controller:  
 $K_S=53.7421, T_I=0.4531, T_3=0.3667$

For injected voltage regulator:  
 $KP_{VAC}=0.0079, KI_{VAC}=0.2655$

For dc voltage regulator:  
 $KP_{VDC}=1.1322 \times 10^{-4}, KI_{VDC}=0.0105$

For power system stabilizer:  
 $K_P=2.3087, T_{1P}=0.1764, T_{3P}=0.2243$

### 5.2 Simulation results

To assess the effectiveness and robustness of the proposed controllers, simulation studies are carried out at different operating conditions under various disturbances. In all figures, the response without control (no control) are shown with dotted line with legend NC; the response with conventionally designed power system stabilizer [1] are shown with dashed lines with legend CP and the response with RCGA optimized proposed controllers are shown with solid line with legend CC respectively. The following cases are considered:

*Case 1: Nominal loading ( $P_e=0.75$  pu,  $\delta_0=45.38^\circ$ )*

A 3-cycle 3-phase fault is applied at the middle of one transmission line at nominal loading condition. 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 figures 5-9. It is clear from these figures that the system is oscillatory and becomes unstable without control under the assumed disturbance and loading condition. With the application of conventional power system stabilizer, these oscillations are effectively suppressed. It is also clear from figures that the proposed RCGA optimized

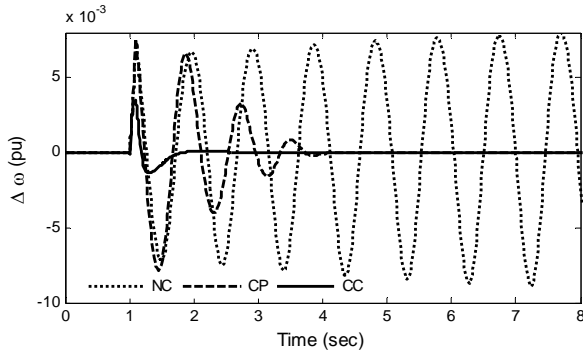


Fig. 5. Speed deviation response for 3-phase fault at transmission line disturbance with nominal loading.

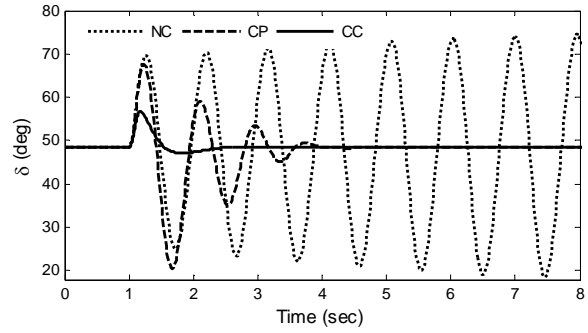


Fig. 6. Power angle response for 3-phase fault disturbance at transmission line with nominal loading.

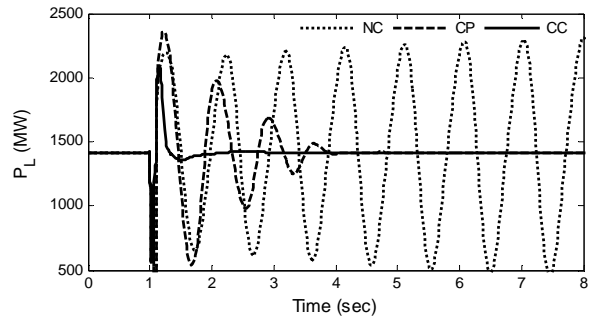


Fig. 7. Tie-line power flow response for 3-phase fault disturbance at transmission line with nominal loading.

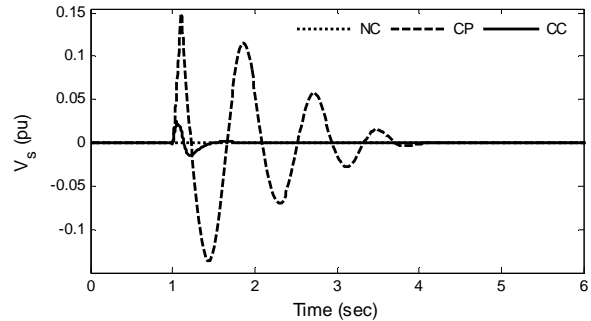


Fig. 8. Stabilizing signal of PSS for 3-phase fault disturbance at transmission line with nominal loading.

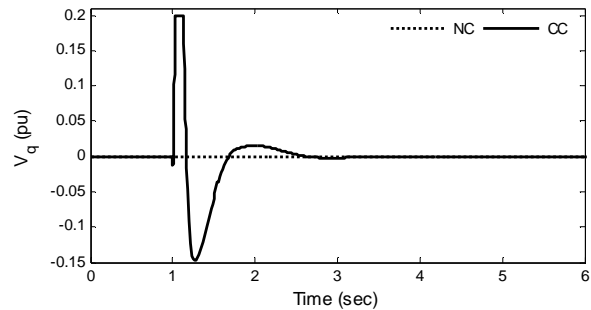


Fig. 9. SSSC injected voltage variation for 3-phase fault disturbance at transmission line with nominal loading.

coordinated stabilizers out perform the conventional PSS from dynamic performance point of view. The power system oscillations are quickly damped out with the coordinated application of proposed controllers.

*Case 2: Heavy loading ( $P_e=1.0 pu, \delta_0=60.72^\circ$ )*

To test the robustness of the proposed controllers to operating condition and fault clearing sequence, the generator loading is changed to heavy loading condition. A 3-phase fault is applied at Bus 2 at  $t=1.0$  sec. The fault is cleared by opening both the lines. The lines are reclosed after 3-cycles and the original system is restored. The system response for the above disturbance is shown in figures 10-12. It is clear from these figures that without control, the system is more

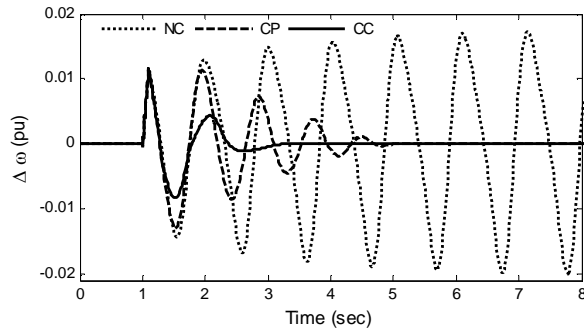


Fig. 10. Speed deviation response for 3-phase fault at Bus 2 with heavy loading.

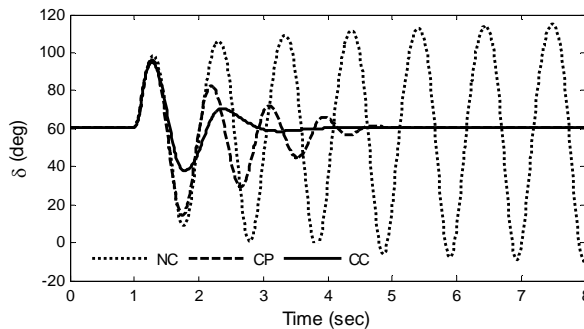


Fig. 11. Power angle response for 3-phase fault at Bus 2 with heavy loading.

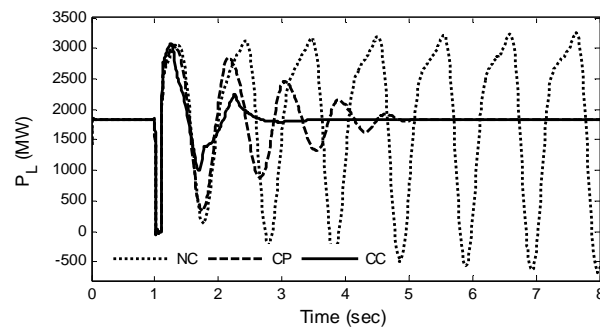


Fig. 12. Tie-line power flow response for 3-phase fault at Bus 2 with heavy loading.

unstable compared to the nominal loading condition and becomes unstable rapidly. With the application of conventional power system stabilizer power system stability is maintained. It is also clear from figures that the proposed RCGA optimized coordinated stabilizers are robust to operating conditions and fault clearing sequence and effectively damps the power system oscillations even at high loading conditions.

*Case 3: Light loading ( $P_e=0.4 pu, \delta_0=22.91^\circ$ )*

The robustness of the proposed controllers is also tested under light loading condition. A 3-phase fault is applied at Bus 3 at  $t=1.0$  sec. The fault is cleared after 3-cycles and the original system is restored after the fault clearance. The system response for the above disturbance is shown in figures 13-14. It can be seen from figures that for the given operating condition and contingency the system is poorly damped without control. It is also clear from figures that the proposed RCGA optimized coordinated stabilizers are robust to operating conditions and fault clearing sequence and quickly damps the power system oscillations compared to conventional power system stabilizer.

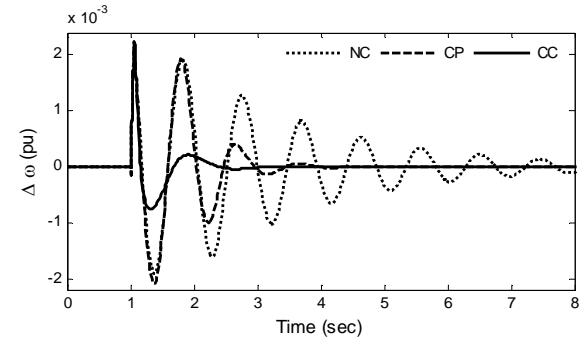


Fig. 13. Speed deviation response for self clearing 3-phase fault at Bus 3 with light loading.

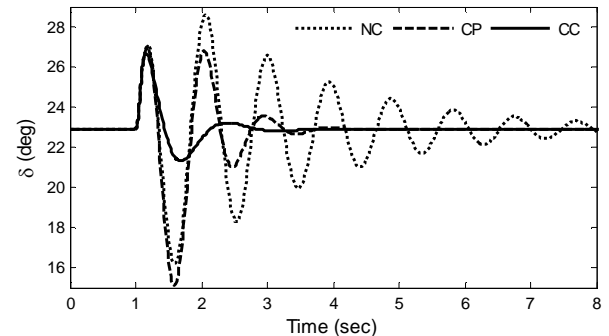


Fig. 14. Power angle response for self clearing 3-phase fault at Bus 3 with light loading.

*Case 4: Small disturbance*

In order to examine the effectiveness of the proposed controller under small disturbance, the load at Bus 1 is disconnected with nominal loading condition at  $t=1$  sec for 100 ms (This simulates a small disturbance). Figures

15-17 show the system response for the above contingency. It is clear from these figures that the system is poorly damped without control under this small disturbance. It is also clear that conventional PSS which is designed for small disturbances is fairly effective in damping the power system oscillations and stabilizing the system under the assumed small disturbance condition. On the other hand, it is evident from the earlier figures (5-7 and 10-14) that conventional PSS perform poorly under large disturbance conditions. However, the proposed controllers which are designed at large disturbance condition perform satisfactorily both for large and small disturbance conditions.

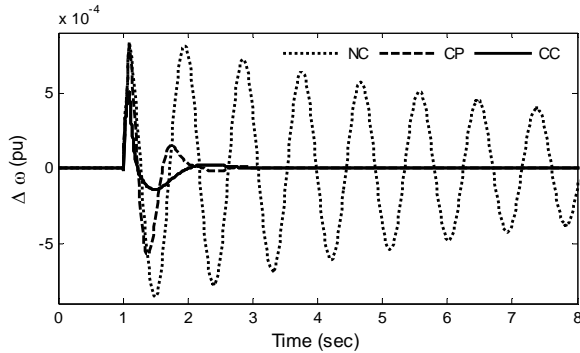


Fig. 15. Speed deviation response for 100 ms load rejection at Bus 1 with nominal loading.

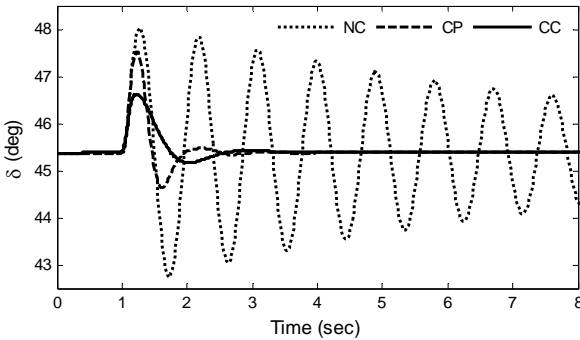


Fig. 16. Power angle response for 100 ms load rejection at Bus 1 with nominal loading.

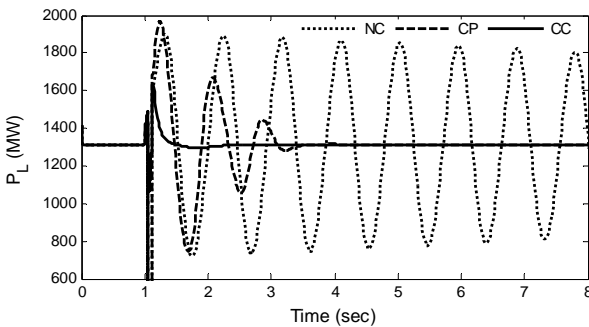


Fig. 17. Tie-line power flow response for 100 ms load rejection at Bus 1 with nominal loading.

### Case 5: Unbalanced fault disturbance

The effectiveness of the proposed controller to unbalanced faults is also examined by applying different types of unsymmetrical faults, namely the double line-to-ground (L-L-G) and single line-to-ground (L-G) faults near Bus3 at  $t = 1$  s with nominal loading condition. The duration of each unbalanced fault is assumed to be of 3-cycles, and the original system is restored after the clearance of the fault. The system power angle response for the above unbalanced contingencies is shown in figure 18, which also shows the uncontrolled response for the least severe fault i.e. single line-to-ground fault. It is clear from figure 18 that even for the least severe fault, the power system oscillations are poorly damped in uncontrolled case. It is also clear that, the proposed coordinated design of PSS and SSSC-based damping controllers is effective under various unbalanced faults and rapidly stabilizes the power angle in all cases disturbance is considered at this loading condition.

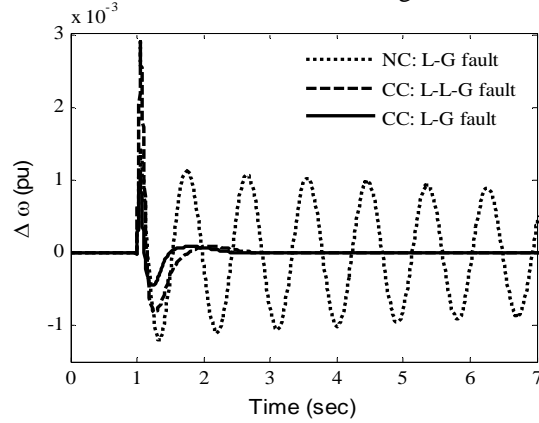


Fig. 18. Speed deviation response for unbalanced faults at Bus 3 with nominal loading.

## 6. Conclusion

In this paper, a real-coded genetic algorithm optimization technique has been employed to coordinately design a PSS and a SSSC-based controller. In the proposed coordinated design approach, along with the PSS and external SSSC-based controller, the SSSC internal ac and dc regulators are also considered. The design problem of proposed controllers is transformed to a non-linear, time-domain simulation-based optimization problem which is solved using a real-coded genetic algorithm. The effectiveness of the proposed controllers which are designed at large disturbance condition is demonstrated under various large and small disturbances as well as unbalanced disturbances. It is observed that the proposed coordinately designed PSS and SSSC-based controllers generate suitable variation of the control signals to provide efficient damping of power system oscillations following a disturbance. Further, the proposed design approach is found to be robust and improves stability effectively under various operating conditions and contingencies. The effectiveness of

proposed controllers under small disturbance and unbalanced fault conditions has also been demonstrated.

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### Appendix

A complete list of parameters used appears in the default options of SimPowerSystems in the User's Manual [12]. All data are in pu unless specified otherwise.

*Generator:*  $S_B = 2100$  MVA,  $H = 3.7$  s,  $V_B = 13.8$  kV,  $f = 60$  Hz,  $R_S = 2.8544 \times 10^{-3}$ ,  $X_d = 1.305$ ,  $X_d' = 0.296$ ,  $X_d'' = 0.252$ ,  $X_q = 0.474$ ,  $X_q' = 0.243$ ,  $X_q'' = 0.18$ ,  $T_d = 1.01$  s,  $T_d' = 0.053$  s,  $T_{qo} = 0.1$  s.

*Load at Bus2:* 250MW

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

*Transmission line:* 3-Ph, 60 Hz, Length = 300 km each,  $R_l = 0.02546 \Omega/\text{km}$ ,  $R_0 = 0.3864 \Omega/\text{km}$ ,  $L_l = 0.9337 \times 10^{-3}$  H/km,  $L_0 = 4.1264 \times 10^{-3}$  H/km,  $C_l = 12.74 \times 10^{-9}$  F/km,  $C_0 = 7.751 \times 10^{-9}$  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,  $\beta = 0$ ,  $T_w = 2.67$  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,  $E_{fmin} = 0$ ,  $E_{fmax} = 7$ ,  $K_p = 0$

*Conventional Power System stabilizer Parameters:* Gain  $K_{PS} = 30$ , Washout time constant  $T_w = 10$  s, Lead-lag structure time constants:  $T_{1CP} = 0.05$  s,  $T_{2CP} = 0.02$  s,  $T_{3CP} = 3$  s,  $T_{4CP} = 5.4$  s, Output limits of  $V_S = \pm 0.15$

*SSSC: Converter rating:*  $S_{nom} = 100$  MVA; System nominal voltage:  $V_{nom} = 500$  kV; Frequency:  $f = 60$  Hz; Maximum rate of change of reference voltage ( $V_{qref}$ ) = 3 pu/s;

*Converter impedances:*  $R = 0.00533$ ,  $L = 0.16$ ; DC link nominal voltage:  $V_{DC} = 40$  kV; DC link equivalent capacitance  $C_{DC} = 375 \times 10^{-6}$  F; Injected voltage magnitude limit:  $V_q = \pm 0.2$

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