

DESIGN COORDINATED CONTROLLER PSS AND TCSC FOR POWER DAMPING OSCILLATIONS USING BACTERIAL FORAGING ALGORITHM

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Abstract

This paper presents an approach for designing power system stabilizer (PSS) and thyristor controlled series capacitor (TCSC) as a damping controller in the single-machine infinite bus for damping low frequency oscillations in a power system using Bacterial Foraging Algorithm (BFA). The problem of robustly PSS and TCSC based damping controller is formulated as an optimization problem according to the eigenvalue-based objective function comprising the damping factor, and the damping ratio of the undamped electromechanical modes to be solved using Bacterial Foraging Optimization (BFA). To ensure the robustness of the proposed stabilizers, the design process takes into account wide range three types of loading light and normal and heavy of operating conditions. The effectiveness of the new controller is demonstrated through eigenvalue analysis studies show that the proposed controller has a good ability in damping power system oscillations.

Introduction

Electromechanical oscillations in power systems are a problem that has been challenging engineers. These oscillations may be very weak damped in some cases, resulting in mechanical fatigue at the machines and Ineligible power variations the across important transmission lines. Therefore, the use of the controllers to provide better damping for these oscillations are of most importance [1]. As power demand grows rapidly and development in transmission and generation is confined with the limited availability of resources and the stringent environmental restrictions, power systems are today much more loaded than before. This causes the power systems to be operated near their stability limits. In addition, inter connection between remotely located power systems gives rise to low frequency oscillations in the range of 0.2–3.0 Hz. If not well damped, these oscillations may keep growing in magnitude until loss of synchronism results [2]. The power systems stabilisers (PSSs) which are widely used for reduction the effects of low frequency oscillation modes improve the performance and functions of power systems during normal and abnormal operations. The PSSs keep the power system in a safe state and protect it from dangerous phenomena. Lately, several advanced control design approaches based on strong control, adaptive control, optimal control and intelligent control have been developed for power system consolidation and oscillation damping [3-5]. The power transfer in an integrated power system is required by voltage stability, small signal stability and transient stability.

These constraints a full utilization of available transmission lines. For minimizing the gap between the stability limit and thermal limit, Flexible AC Transmission System (FACTS) is the technology that provides the needed reform of the transmission agency in order to fully utilize the existing transmission equipment [6]. FACTS devices can do by controlling the power flow along the transmission lines and improving power oscillations damping [7-8]. The use of these controllers increases the flexibility of the operation by providing more options to the power system operators. Between the available FACTS devices for transient stability increase, the TCSC is one of the best [9-11]. The TCSC is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. In dynamic application of the TCSC, various control techniques and designs have been proposed for damping power oscillations to improve the system dynamic response [7, 9]. At [7, 12] used fuzzy logic based damping control strategy for TCSC, UPFC and SVC in a multi-machine power system. The damping control strategy employs non-optimal fuzzy logic controllers that is why the system's response settling time is intolerable. Also, the initial parameters regulation of this type of controller needs some trial and error. Vice versa the other heuristic techniques, it has a flexible and well balanced mechanism to enhance the global and local search abilities. Also, it is enough to specify the objective function and to place limited boundaries on the optimized parameters. The applications of TCSC for power oscillation damping and stability increase can be found in [13]. The power system stability increase via PSS and TCSC based stabilizer when applied independently and also through coordinated application is discussed in [14]. A pole placement technique for PSS and TCSC based stabilizer using simulated annealing (SA) algorithm is presented in [15]. A method for modeling and tuning the parameters of TCSC compensation controller in a multi-machine power system to improve system stability using GA is proposed in [16]. The application and performance comparison of PSO and GA optimization techniques, for FACTS based controller design is treated in [17]. A other design procedure for simultaneous coordination designing of the TCSC damping controller and PSS in multi-machine power system is developed in [18] using particle swarm optimization (PSO). A novel scheme of damping power system multi-mode oscillations by using a single FACTS device is illustrated in [19].

In this paper, a Single Machine Infinite Bus (SMIB) power system installed with a TCSC and PSS is considered for case study and BFA is used to design TCSC and PSS controller parameters. The problem of the controller design is formulated as an optimization problem and BFA is used to solve it. The effectiveness of the proposed controller is demonstrated through

simulation results and eigenvalues analysis for three types range of loading light and normal and heavy of operating conditions and Fault at transmission line.

I. Bacterial Foraging Algorithm (BFA)

The idea of BFA is based on the fact that natural selection tends to eliminate animals with poor foraging strategies and favor those having successful foraging strategies. After many generations, poor foraging strategies are either eliminated or reshaped into good ones. E.coli bacteria that are present in our intestines have a foraging strategy governed by four processes, namely, chemotaxis, swarming, reproduction, and elimination and dispersal [20].

A. Chemotaxis

This process is achieved through swimming and tumbling. Depending upon the rotation of the flagella in each bacterium, it decides whether it should move in a predefined direction (swimming) or an altogether different direction (tumbling), in the entire life time of the bacterium.

To represent a tumble, a unit length random direction, say, $\phi(j)$, is generated; this will be used to define the direction of movement after a tumble.

In particular

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + C(i)\phi(j) \quad (1)$$

Where $\theta^i(j, k, l)$ represents the i th bacterium at j th chemotactic, k th reproductive, and l th elimination and dispersal step. $C(i)$ is the size of the step taken in the random direction specified by the tumble (run length unit).

B. Swarming

During the process of reaching toward the best food location, it is always desired that the bacterium which has searched the optimum path should try to provide an attraction signal to other bacteria so that they swarm together to reach the desired location. In this process, the bacteria congregate into groups and, hence, move as concentric patterns of groups with high bacterial density. The mathematical representation for swarming can be represented by:

$$\begin{aligned} J_{cc}(\theta, P(j, k, l)) &= \sum_{i=1}^S J_{cc}^i(\theta, \theta^i(j, k, l)) \\ &= \sum_{i=1}^S \left[-d_{attract} \exp(-\omega_{attract} \sum_{m=1}^P (\theta_m - \theta_m^i)^2) \right] \\ &= \sum_{i=1}^S \left[h_{repellent} \exp(-\omega_{repellent} \sum_{m=1}^P (\theta_m - \theta_m^i)^2) \right] \end{aligned} \quad (2)$$

Where $J_{cc}(\theta, P(j, k, l))$ is the cost function value to be added to the actual cost function to be minimized to present a time varying cost function. "S" is the total number of bacteria. "P" is the number of parameters to be optimized that are present in each bacterium. $d_{attract}$, $\omega_{attract}$, $h_{repellent}$, and $\omega_{repellent}$ are different coefficients that are present that are to be chosen judiciously.

C. Reproduction

The least healthy bacteria die, and the other healthiest bacteria each split into two bacteria, which are placed in the same location. This makes the population of bacteria constant.

D. Elimination and Dispersal

It is possible that in the local environment, the life of a population of bacteria changes either gradually by consumption of nutrients or suddenly due to some other influence. Events can kill or disperse all the bacteria in a region. They have the effect of possibly destroying the chemotactic progress, but in contrast, they also assist it, since dispersal may place bacteria near good food sources. Elimination and dispersal helps in reducing the behavior of stagnation (i.e., being trapped in a premature solution point or local optima). The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [20, 21]. (See Appendix A).

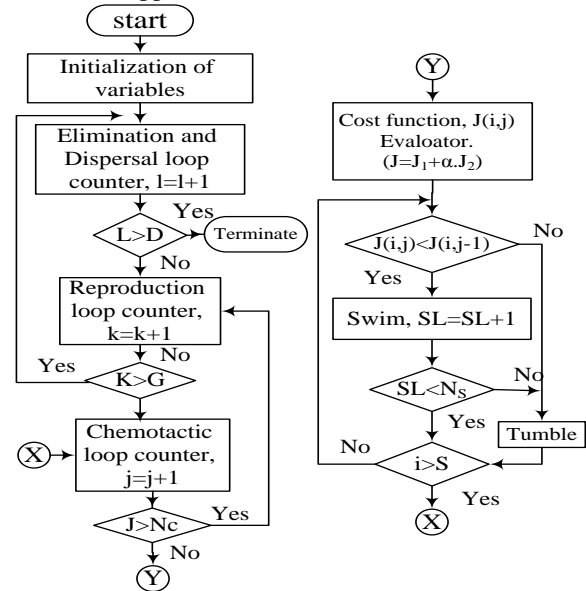


Figure 1. Flowchart of Bacterial Foraging Algorithm

II. Power System Model

The single machine infinite bus (SMIB) power system installed with a TCSC, shown in figure 2 is considered in this study.

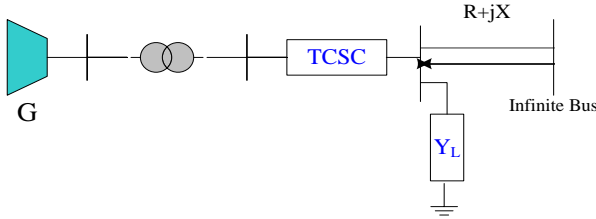


Figure 2. Single Machine Infinite Bus System with a TCSC

In the design of electromechanical mode damping stabilizer, a linearized incremental model around an operating point is usually employed [6]. The Phillips-Heffron model of the power system with TCSC and PSS is obtained by linearizing nonlinear equations of the power system around an operating condition. The linearized expressions are as follows:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \\ \dot{\Delta E'_q} \\ \dot{\Delta E_{fd}} \end{bmatrix} = \begin{bmatrix} 0 \\ -K_p/M \\ -K_Q/M \\ -K_V/M \end{bmatrix} \Delta\sigma +$$

$$\begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -K_1/M & -D/M & -K_2/M & 0 \\ -K_4/T'_{do} & 0 & -K_3/T'_{do} & 1/T'_{do} \\ -K_A K_5/T_A & 0 & -K_A K_6/T_A & -1/T_A \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} \quad (3)$$

Where:

$$K_1 = \partial P_e / \partial \delta, K_2 = \partial P_e / \partial E'_q, K_3 = \partial E_q / \partial E'_q$$

$$K_4 = \partial E_q / \partial \delta, K_5 = \partial V_T / \partial \delta, K_6 = \partial V_T / \partial \sigma$$

$$K_V = \partial V_T / \partial \sigma, K_p = \partial P_e / \partial \sigma, K_Q = \partial E_q / \partial \sigma,$$

$$P_e = V_{td} I_{td} + V_{tq} I_{tq}; E_q = E'_{qe} + (X_d - X'_d) I_{td}$$

$$V_t = V_d + jV_q; V_{td} = X_q I_{tq}; V_{tq} = E'_q - X'_d I_{td}$$

$$I_{td} = I_{tld} + I_{Ed} + I_{Bd}; I_{tq} = I_{tlq} + I_{Eq} + I_{Bq}$$

$$K_q = ((X'_d - X'_d) \times (E'_q - V_b \times \cos^{-1} \delta) \times (X_c \times (1 - \cos^{-1} \beta))) / X_2^2$$

$$K_p = (I_q \times (X_q - X'_d) \times ((E'_q - V_b \times \cos^{-1} \delta) \times X_c \times (1 - \cos^{-1} \beta))) / X_2^2 +$$

$$((E'_q + V_b \times \sin^{-1} \delta) \times X_c (1 - \cos^{-1} \beta) \times (E'_q + (X'_d - X'_d) \times I_{td})) / X_L^2$$

$$K_V = ((V_d / V_t) \times (X_q \times (E'_q + V_b \times \sin^{-1} \delta) \times X_c \times (1 - \cos^{-1} \beta))) / (X_L^2) -$$

$$(((V_q / V_t) \times X'_d \times X_c \times (1 - \cos^{-1} \beta) \times (E'_q - V_b \times \cos^{-1} \delta))) / X_2^2$$

The Phillips-Heffron model of the SMIB system with PSS and TCSC is obtained using the linearized equations. The corresponding block diagram model is shown in figure 3.

III. Structure of the Proposed Stabilizers

A conventional lead-lag controller structure for both PSS and TCSC as shown in Figs. 4 and 5 and 6 is considered in this study.

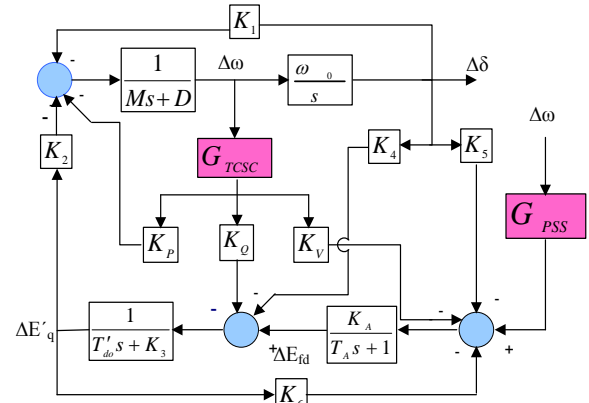


Figure 3. Block Diagram of the Linearized Power System Model

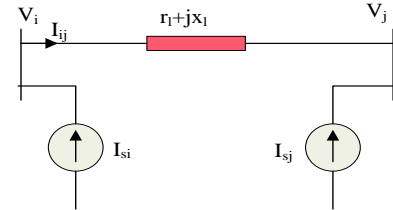


Figure 4. Current Injection Model for a TCSC

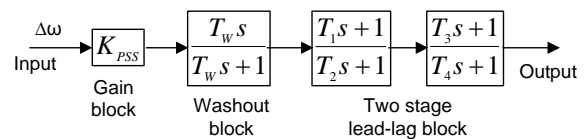


Figure 5. Structure of Power System Stabilizer

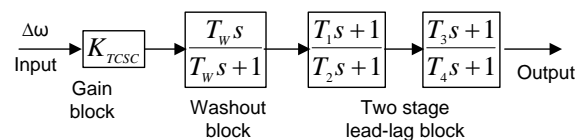


Figure 6. Thyristor Controlled Series Capacitor

The stabilizing signals of the proposed PSS and TCSC can be expressed as:

$$U_{PSS} = K_{PSS} \frac{sT_W}{1+sT_W} \left(\frac{1+sT_{1PSS}}{1+sT_{2PSS}} \right) \left(\frac{1+sT_{3PSS}}{1+sT_{4PSS}} \right) \Delta\omega \quad (4)$$

$$U_{TCSC} = K_{TCSC} \frac{sT_W}{1+sT_W} \left(\frac{1+sT_{1TCSC}}{1+sT_{2TCSC}} \right) \left(\frac{1+sT_{3TCSC}}{1+sT_{4TCSC}} \right) \Delta\omega \quad (5)$$

To increase the system damping to the electromechanical modes, the objective function J defined below is proposed.

$$J = \sum_{\sigma_i \geq \sigma_0} (\sigma_0 - \sigma_i)^2 \quad (6)$$

Where σ_i is the real part of the i^{th} eigenvalue and σ_0 is a chosen threshold. The value of σ_0 represents the desirable level of system damping. This level can be achieved by shifting the dominant eigenvalues to the left of $s = \sigma_0$ line in the s-plane. This insures also some degree of relative stability. The condition $\sigma_i \geq \sigma_0$ is imposed on J evaluation to consider only the unstable or poorly damped modes. The problem constraints are the parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Minimize J

Subject to

$$\begin{aligned} K_{PSS}^{\min} \leq K_{PSS} \leq K_{PSS}^{\max} ; T_{1PSS}^{\min} \leq T_{1PSS} \leq T_{1PSS}^{\max} \\ T_{2PSS}^{\min} \leq T_{2PSS} \leq T_{2PSS}^{\max} ; T_{3PSS}^{\min} \leq T_{3PSS} \leq T_{3PSS}^{\max} \\ T_{4PSS}^{\min} \leq T_{4PSS} \leq T_{4PSS}^{\max} ; K_{1TCSC}^{\min} \leq K_{1TCSC} \leq K_{1TCSC}^{\max} \\ T_{1TCSC}^{\min} \leq T_{1TCSC} \leq T_{1TCSC}^{\max} ; T_{2TCSC}^{\min} \leq T_{2TCSC} \leq T_{2TCSC}^{\max} \\ T_{3TCSC}^{\min} \leq T_{3TCSC} \leq T_{3TCSC}^{\max} ; T_{4TCSC}^{\min} \leq T_{4TCSC} \leq T_{4TCSC}^{\max} \end{aligned}$$

The minimum and maximum values of the controller gain share set as 0.01 and 100, respectively.

IV. Simulation Results

To assess the effectiveness and robustness of the proposed stabilizers, three different loading conditions given in Table 1 were considered with different disturbances (see Appendix B).

Table 1. Loading Conditions

Loading	P (p.u)	Q (p.u)
Nominal	0.8	0.1
Light	0.6	0.05
Heavy	1	0.2

Case1. Step Response for Nominal Load Condition

At these loading conditions, the system eigenvalues with and without the proposed stabilizers are given in Table 2. It is shown that the open loop system is unstable because of the negative damping of electromechanical mode. It is quite clear that the proposed stabilizers are better and shift substantially the electromechanical mode eigenvalue to the left in the s-plane. This enhances greatly the system stability and improves the damping characteristics of electromechanical mode. The system response is shown in Figs. 7-9. It can be seen that the response of PSS&TCSC stabilizer is much faster than of other Stabilizers. In addition, the first swing in the torque angle is significantly suppressed and the voltage profile is greatly improved with the proposed PSS&TCSC. Because, the model under study is a linear to evaluate the system response in case of an error, a line parallel to the ground and how the system responds to faults in the presence of TCSC are examined at Figs. 10-12. As can be inferred from Table 2 that the curve of eigenvalues in the presence of TCSC controller electromechanical changes have been damped in the fastest time possible.

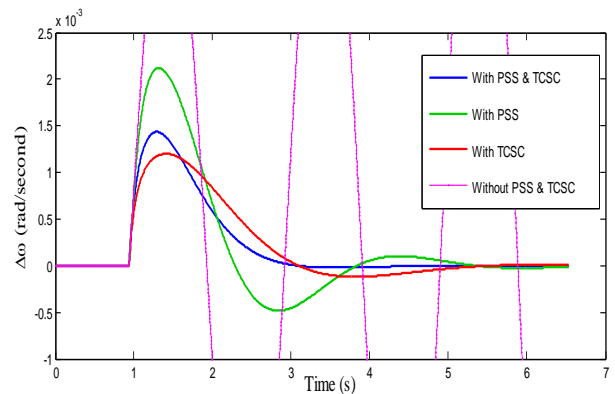


Figure 7. Response of $\Delta\omega$ for Nominal Load.

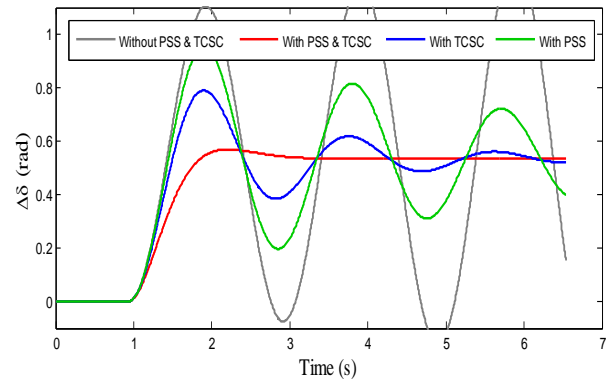


Figure 8. Response of $\Delta\delta$ for Nominal Load.

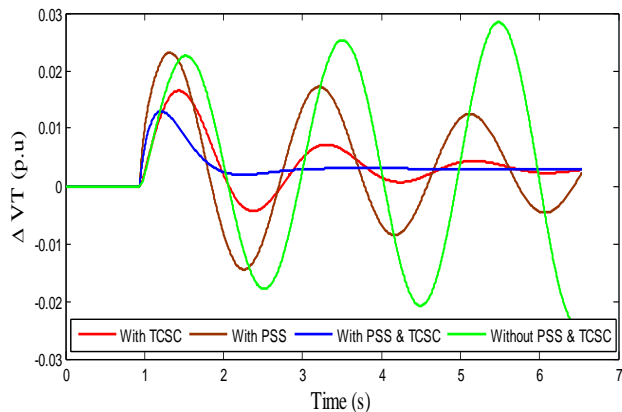


Figure 9. Response of ΔV_T for Nominal Load.

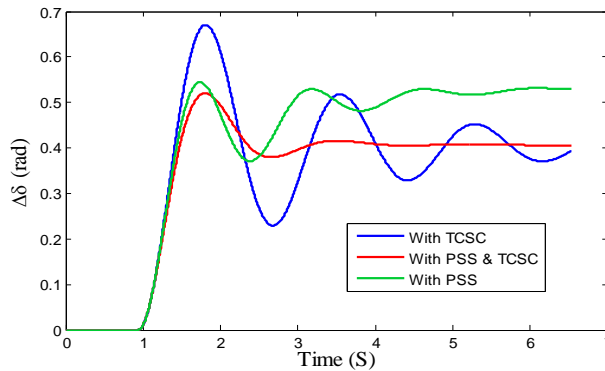


Figure 11. Response of $\Delta\delta$ for Fault in Nominal Load.

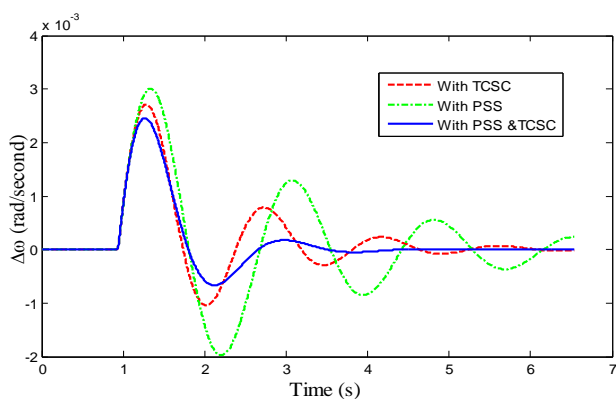


Figure 10. Response of $\Delta\omega$ for Fault in Nominal Load.

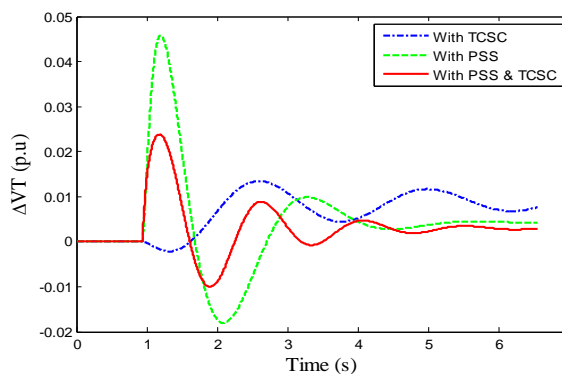


Figure 12. Response of ΔV_T for Fault to Nominal Load.

Table 2. Mechanical Modes Nominal Loading Conditions and Controllers.

Without control	With PSS	With TCSC	Fault SMIB with TCSC	With PSS and TCSC
-91.2735	-93.0859	-73.1648	-78.8608	-73.1512
0.0279 + 3.0127i	-3.4515 + 12.0848i	-26.7122	-21.3155	-26.7545
0.0279 - 3.0127i	-3.4515 - 12.0848i	-0.1069	-0.4524 + 3.3662i	-1.9441 + 1.2818i
-9.1688	-0.1331	-2.5297 + 1.0194i	-0.4524 - 3.3662i	-1.9441 - 1.2818i
	-0.3940	-2.5297 - 1.0194i	-0.1010	-2.3135 + 0.9777i
	-2.3629	-2.6221 + 0.4400i	-2.5218 + 0.0512i	-2.3135 - 0.9777i
	-2.6478	-2.6221 - 0.4400i	-2.5218 - 0.0512i	-2.3456
				-33.6793

Case2. Step Response for Light Load Condition

Figs. 13-15, show the system response for a 0.1 step increase in mechanical torque of generator for light loading condition. These figures indicate the capability of the propose coordinated controllers in reducing the settling time and damping power system oscillations. Moreover, this figures demonstrates that the proposed algorithm is outperforms. At these loading conditions, the system eigenvalues with and without the proposed stabilizers are given in Table 3.

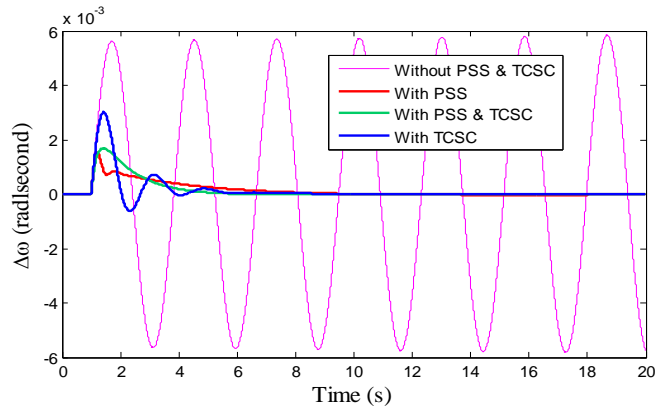


Figure 13. Response of $\Delta\omega$ for Light Load.

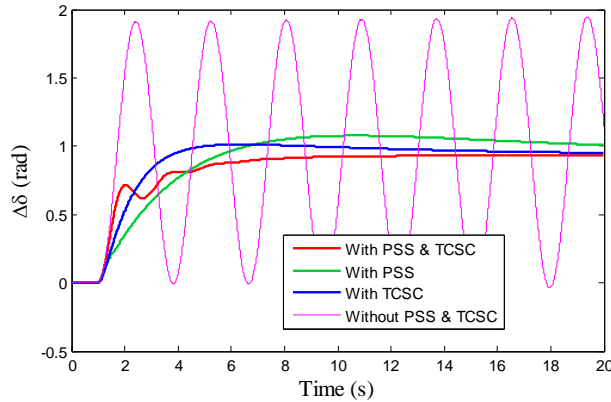


Figure 14. Response of $\Delta\delta$ for Light Load.

Table 3. Mechanical modes Light loading conditions and controllers.

Without control	With PSS	With TCSC	Fault with TCSC	With PSS and TCSC
-91.4467	-92.3266	-74.7848	-78.7650	-75.0259
$0.1275 + 2.8215i$	$-3.8614 + 9.7493i$	-25.1945	-25.0468	-24.5341
$0.1275 - 2.8215i$	$-3.8614 - 9.7493i$	$-0.1336 + 2.8736i$	$-0.9382 + 9.9766i$	$-0.9319 + 3.6027i$
-9.1951	-0.1631	$-0.1336 - 2.8736i$	$-0.9382 - 9.9766i$	$-0.9319 - 3.6027i$
	-0.2565	-1.7717	$-1.0391 + 1.0243i$	-0.4829
	-2.3618	-0.2594	$-1.0391 - 1.0243i$	-1.2218
	-2.6491	-0.1327	-0.1050	-1.9478 & -1.7348

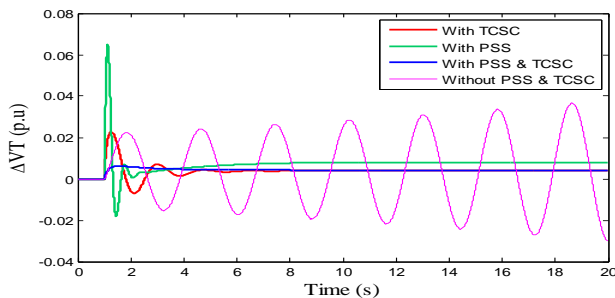


Figure 15. Response of ΔV_T for Light Load.

shown in Figs.16-18. Also, this controller has a simple architecture and the potentiality of implementation in real time environment.

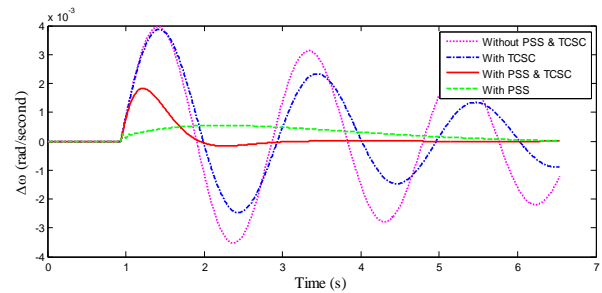


Figure 16. Response of $\Delta\omega$ for Heavy Load.

Case 3. Step Response for Heavy Load Condition

Figs. 16-18, show the system response at heavy loading condition with fixing the controller parameters. From these figures, it can be seen that the response with the proposed coordinated controllers shows good damping characteristics to low frequency oscillations and the system is more quickly stabilized than PSS and TCSC. At these loading conditions, the system eigenvalues with and without the proposed stabilizers are given in Table 4. Hence, the simulations results reveal that the simultaneous coordinated designing of the TCSC damping controller and the PSS demonstrates its superiority to both the uncoordinated designed controllers of the PSS and the TCSC at large disturbance as

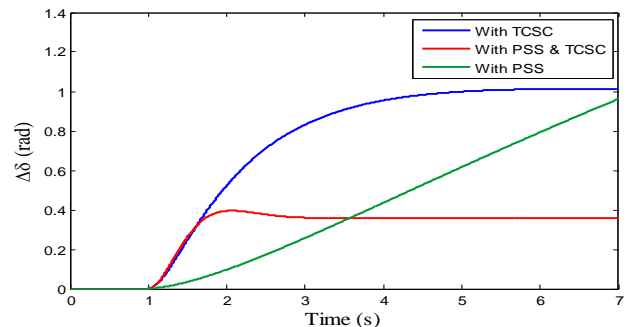


Figure 17. Response of $\Delta\delta$ for Heavy Load.

Table 4. Mechanical Modes Heavy Loading Conditions and Controllers.

Without control	With PSS	With TCSC	Fault with TCSC	With PSS and TCSC
-91.2243	-93.4027	-74.8341	-78.6902	-72.7282
-0.1143 + 3.0417i	-3.4618 +13.2373i	-25.0350	-21.2402	-24.6576
-0.1143 - 3.0417i	-3.4618 -13.2373i	-5.2465	-0.0552 + 4.5106i	-2.4718 + 2.8392i
-8.9337	-0.0683 + 0.0926i	-0.1160	-0.0552 - 4.5106i	-2.4718 - 2.8392i
	-0.0683 - 0.0926i	-0.8645	-1.2856	-2.2518 + 0.5238i
	-2.3792	-2.2519	-0.6806	-2.2518 - 0.5238i
	-2.6378	-2.7206	-0.1028	-2.4944 & -2.5132

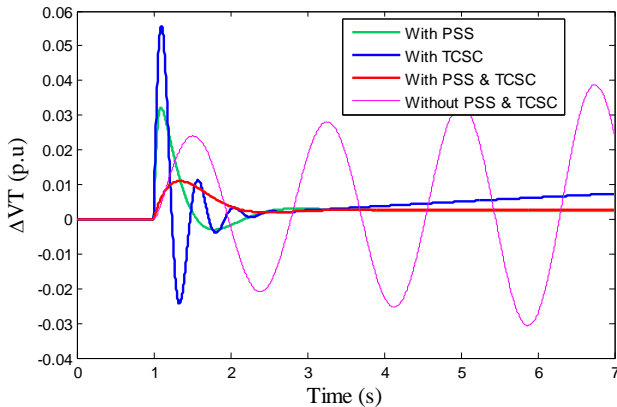


Figure 18. Response of ΔV_T for Heavy Load.

Conclusions

In this paper, a robust design algorithm for the simultaneous coordinated tuning of the TCSC damping controller and PSS in single machine infinite bus proposed. The design problem of the proposed controllers is formulated as an optimization problem and BFA is employed to search for optimal controllers parameters. Simulations results have shown that the mechanism of BFA allows for faster and more efficient convergence. The eigenvalues analysis and simulation results show that the proposed controller has good performance on damping low frequency oscillations and improves the transient stability under different operating conditions.

Appendix A. Single-Machine Infinite-Bus Power System

System data: All data are in p.u unless specified otherwise.

Generator: $M=8.0$; $D=0.0$; $T'_d=5.044$; $X_d=1$; $X_q=0.5$; $X'_q=0.3$.

Exciter: $K_A=50$; $T_A=0.01$

Transmission line and transformer: $X_L=0.5$; $X_{TG}=0.0$; $R=0.0$; $X_T=0.2$.

Appendix B. BFA algorithm parameters are adjusted

dimension of optimization process	5
number of bacteria	2
number of chemotactic step	40
number of swimming step	20
number of reproduction	20
number of elimination and dispersal	1
probability index of elimination and dispersal	1
step size for each bacterium	0.09

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