International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

September 2013 Issue 16 Volume 5 Number 3 Pages 64-72

COLLABORATION OF PSS AND TCSC CONTROLLERS IN MULTIMACHINE AREA TO MITIGATE POWER SYSTEM OSCILLATIONS

B. Khorram [1] **H. Lesani** [2] **J. Olamaei** [1]

1. Department of Electrical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran
b_khorram@yahoo.com, j_olamaei@azad.ac.ir
2. Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran, lesani@ut.ac.ir

Abstract- Simultaneous incorporated application of Thyristor Controlled Series Capacitor (TCSC) and Power System Stabilizers (PSSs) in multi-machine power systems under different loading conditions is presented in this paper. As a search strategy, the Imperial Competitive Algorithm (ICA) is used to find the parameters of optimal controllers. For the purpose of enhancing system stability performance the recommended objective function, containing the speed deviations between generators, has to be minimized. For comparison, the application of PSS and TCSC exclusively and then together is tested. The results indicate that simultaneous usage of incorporating controllers based on bacterial swarm has damping performance more robust than exclusive application of optimized PSS controller based on ICA (ICAOPSS) and optimized TCSC controller based on ICA (ICATCSC) under different disturbances and in a wide range of operating conditions. Furthermore, the results are calculated with the Bacteria Foraging Optimization Algorithm (BFOA) as well as Genetic Algorithm (GA), which concludes the superiority of ICA over the other methods to achieve a global optimal solution.

Keywords: Imperialist Competitive Algorithm (ICA), PSS and TCSC Design, Multi-Machine Power System, BFOA, GA.

I. INTRODUCTION

In massive power systems, slow oscillations may occur because of poor connections bye tie lines. Damping is a significant parameter in controlling these oscillations, which may separate the system [1, 2]. Recently, power systems utilize Conventional Power System Stabilizer (CPSS) to a large degree. It should be noted that different loads alter the machine parameters complicatedly. Therefore, in sudden changes of operating conditions, steady parameters of stabilizers might not give satisfactory outcomes. Therefore, the system should be robust partly to changes in its parameters, loading conditions, and configurations deals with robust PSS design using H_1 optimization methods, presenting significance and problems in choosing weighting functions [3, 4].

Furthermore, after perturbation the system becomes unstable in which the additive and / or multiplicative uncertainty representation may not be useful [5]. Besides, the problem of closed loop poles damping rises as the result of pole-zero cancellation that is related to the open loop system [6]. Moreover, in high order plants, which will cause complicated H_1, based stabilizers of the same order are not applicable. Impression of various CPSS parameters on dynamic efficiency of power system is introduced inclusively in [7]. Proper selection of these parameters leads to acceptable performance after perturbation.

To optimize PSS parameter in multi-machine power systems different approaches have been used such as Genetic Algorithm [8, 9], Tabu Search (TS) [10], Simulated Annealing (SA) [11], Particle Swarm Optimization (PSO) [12-14], and Bacterial Foraging (BF) [15]. The problem is that the search process may stagnate in a local minimum. In some situations, damping made by additional stabilizing signals may not be enough. So choices other than PSS should be considered. Modern power electronics presents Flexible AC Transmission Systems (FACTS) controllers in power systems.

The exclusive ability of FACTS controllers to manage the fast variations in network enhances the stability of the power system. More comprehensive information on FACTS controllers are provided in [16-18]. Thyristor Controlled Series Compensators (TCSC) is one famous member of FACTS devices widely used in today's long line power systems. It plays an important part in such systems including, adjusting power flow, restricting short circuit currents, net loss reduction, enable voltage support, mollifying Sub-Synchronous Resonance (SSR), damping the power oscillation, raising transient stability [17].

In [16-22] the damping power oscillation and raising stability features of the TCSC, in jus Single Machine Infinite Bus (SMIB) system is studied. FACTS devices probabilistic modeling and total transfer estimation are given in [23]. A reduced rule base Self-Tuning Fuzzy PI Controller (STFPIC) for TCSC is proposed in [24]. Virtual Bees Algorithm (VBA) employed for additional control of damping for TCSC is presented in [25].

The optimal location and design values of TCSC in order to play down the losses, *L*-index and voltage profile enhancement, utilizing BF is proposed in [26]. Multi-objective evolutionary algorithm in FACTS based stabilizers using PID controller is illustrated in [27].

There has been little effort to the collaboration of PSS and TCSC controller in multi-machine power systems. The application of PSS and TCSC exclusively or together in augmentation of system stability is explored in [28]. An SA based pole placement method is presented for PSS and TCSC based stabilizers in [29]. In some studies the enhancement of system stability using both PSS and TCSC through GA and PSO are covered [30, 31]. To achieve better stability, transient and steady state response in nonlinear systems inclusive of PSS and of an Interline Power Flow Controller (IPFC) by BF is discussed in [32].

The outcome of an optimal controller to particular types of disturbances is contrasted with the ones obtained from GA to conclude the efficiency of BF in global optimization of the controller. However, these experimentations are restricted for SMIB system. Although GA works well in global optimization problem, the very long run time is an obstacle to be overcome. This time varies from some minutes to hours according to the system's size. Another deficiency is the lack of investigating the performance of each device when working exclusively or together with other devices. In multi-machine power system, damping controller based on TCSC and PSS by employing PSO is disclosed in [33].

In recent years, many different optimization methods by means of swarming principle have been proposed in different fields of engineering. The application of swarming strategies in bird flocking and fish schooling in PSO is discussed in [34]. Quiet newer algorithm named BF scheme is introduced in [35-37] and more developed in [38, 39]. A contemporary study, BF oriented by PSO integrating all the referred optimization algorithms is presented in [40, 41]. In this paper, the focus is on the investigation of PSS and RCSC based controllers, when applied exclusively and altogether. To enhance the stability of power system through usage of PSS and TCSC based controller is converted to an optimization problem.

The purpose is to enhance stability of a multi-machine power system in the presence of disturbance. The optimal solutions for controllers based on PSS and TCSC is found by BSO technique. BSO based TCSC controller (BSOTCSC) and BSO based PSS (BSOPSS) controller are developed and evaluated over the application of BSOPSS and BSOTCSC exclusively. The efficiency of the proposed method to enhance the stability of power system is assessed through some series of simulations.

II. PROBLEM STATEMENT

A. Power System Model

A power system can be modeled by a set of nonlinear differential equations as follow:

$$\dot{X} = f(X,U) \tag{1}$$

where, $X = [\delta, \omega, E'_q, E_{fd}, V_f]^T$ is vector of state variables, U is PSS and TCSC output signals, δ and ω are rotor angle and speed, respectively, E'_q, E_{fd} and V_f are internal, field, and excitation voltages, respectively.

The problem of PSS and TCSC design is solved around equilibrium point by means of linearized incremental model. A power system with n machines and m PSS and TCSC can be modeled as:

$$\dot{X} = AX + Bu \tag{2}$$

where, $A = \partial f / \partial X$ is a $5n \times 5n$ matrix, $B = \partial f / \partial U$ is a $5n \times m$ matrix which are both assessed in a specific operating point, X is a $5n \times 1$ state vector and U is an $m \times 1$ input vector.

Figure 1 demonstrates the single line diagram of the case study. Details of system data are given in [42]. To distinguish different modes the participation matrix is employed. In Table 1 the eigenvalues and frequencies, dealing with the rotor oscillation modes of the system is illustrated. As seen in this table, the 0.2371 Hz mode is the inter-area mode with G1 oscillating against G2 and G3. The 1.2955 Hz and 1.8493 Hz modes are the inter-machine oscillation local to G2 and G3 respectively. The system instability is declared by the positive real part of G1's eigenvalue. The loading levels of system and generator are presented in Table 2.

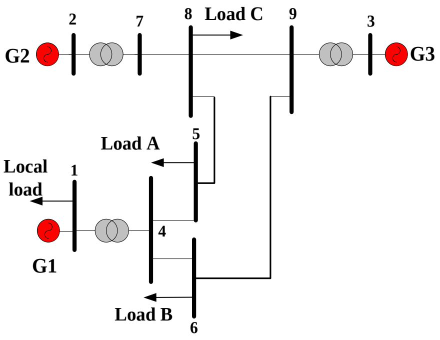

Figure 1. System under study

Table 1. The proper values and frequencies connected to the rotor oscillation mode of the system

Generator	Eigenvalues	Frequencies	Damping ratio ζ
G1	$+0.15 \pm 1.49j$	0.2371	-0.1002
G2	$-0.35 \pm 8.14j$	1.2955	0.0430
G3	$-0.67 \pm 11.62j$	1.8493	0.0576

Table 2. Loading condition for the system

Generator	Light		Normal		Heavy	
	P	*Q*	*P*	*Q*	*P*	*Q*
G1	0.96	0.223	1.716	0.620	3.57	1.814
G2	1.00	-0.193	1.630	0.066	2.20	0.712
G3	0.45	-0.266	0.850	0.108	1.35	0.431
Load						
A	0.70	0.35	1.25	0.50	2.00	0.900
B	0.50	0.30	0.9	0.300	1.80	0.600
C	0.60	0.20	1.00	0.350	1.60	0.650
Local load	0.60	0.20	1.00	0.350	1.60	0.650

B. PSS Structure

The PSS's functionality is to create an appropriate torque on the rotor, so that electrical torque and input of the exciter's phase lag is compensated. In this paper a common PSS, based on speed, which is proportional to the additional stabilizer, is applied [7]. The ith PSS is illustrated in the form of block diagrams in Figure 2. In which $\Delta\omega_i$ is the synchronous speed deviation. This kind of stabilizer comprises a washout filter and a dynamic compensator. The excitation system employs a regulator with an input fed back from the output signal. The washout filter has to be a high pass one and is used to remove the output offset in the steady state. The time constant T_w, differs in range between 0.5 to 20 s. Two lead lag circuits in series with an extra gain constitute the dynamic compensator.

The PSS's controllable parameters include the gain of the PSS, K_i and the time constants, T_{1i} - T_{4i}. In the system's circuit, there is a phase lag betwixt the exciter input and the electrical torque. The compensation is done by the lead lag block available in the system. Despite the fact that the dominator section including T_{2i} and T_{4i} produces a constant lag angle, lead lag circuit can create the desired phase lead.

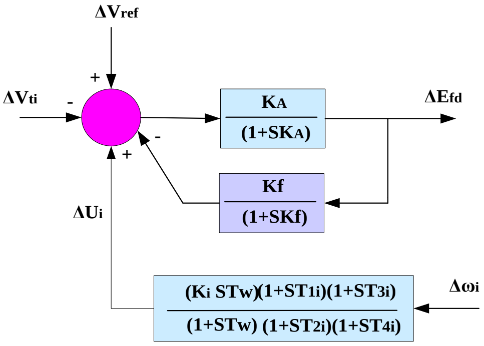

Figure 2. Block diagram of *i*th PSS

C. TCSC Structure

The parallel combination of a Thyristor Controlled Reactor (TCR) and a constant capacitor constructs a typical TCSC module. A bi-directional thyristor valve is fired by a phase angle limited between 90 to 180 considering the capacitor's voltage. This thyristor in series with a reactor comprises the TCR. In dynamic stability and load flow inquisition, a TCSC can be expressed as a variable reactance in form of the equation coming after:

$$\Delta\dot{X}_{TCSC} = \frac{1}{T_s(K_s(\Delta X_{TCSC}^{ref} + \Delta U_{TCSC})} \tag{3}$$

where, ΔX_{TCSC}^{ref} is the reference reactance of the TCSC, K_s gain and T_s time constant of TCSC.

The TCSC based damping controller deemed as a lead lag compensator consists of gain, signal washout block and two stages of lead lag compensator, as shown in Figure 3. Damping controllers' parameters are designated for the simultaneous incorporated application by means of BSO algorithm.

Different kinds of signals, such as those with precious information about the inter-area mode could be employed as the input signal for the FACTS to damp the system oscillations. Local input signals would be a better choice as the result of FACTS controllers' location in transmission system. Line active power and current for instance will hold important information.

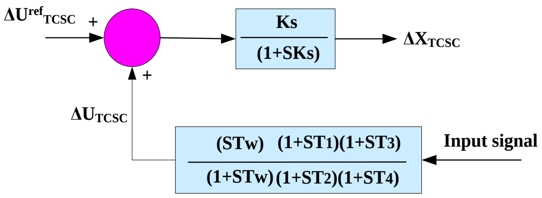

Figure 3. Block diagram of TCSC

A useful choice of input signal applied in [33, 43] is the transmission line active power in FACTS based damping controllers in series. In this study, transmission line active power is employed as the input. In Table 3, the line flow data is illustrated. Line 5-7 has the maximum power flow as well as biggest length in the proposed system. Therefore, this line would be considered as the best place for TCSC controllers' installation.

Table 3. Base case (line flow) on 100 MVA base

From Bus	To Bus	Real Power (pu)
4	6	0.3070
6	9	0.6082
4	5	0.4094
5	7	0.8662
7	8	0.7638
8	9	0.2410

III. FITNESS FUNCTION

The main aim here is to coordinated design of PSS and TCSC via ICA technique. Optimization is used to seek the optimum controller parameters so as to improve the system damping properties. For this purpose, the design problem can be formulated with the following fitness function, which is based on the Integral of Time Multiple Absolute Error (*ITAE*) as follow:

$$FF = \int_{t_0}^{t} t(|\Delta\omega_{12}| + |\Delta\omega_{23}| + |\Delta\omega_{13}|)dt \tag{4}$$

where, $\Delta\omega_{12} = \Delta\omega_1 - \Delta\omega_2$, $\Delta\omega_{23} = \Delta\omega_2 - \Delta\omega_3$, and $\Delta\omega_{13} = \Delta\omega_1 - \Delta\omega_3$. The major goal is to minimize the J:

$$FF : \text{minimize}(J) \tag{5}$$

In order to reduce the computational difficulty, the value of T_w is assumed 10 sec, the values of T_{2i} and T_{4i} are kept constant at a reasonable value of 0.05 s and adjusting of T_{1i}, T_{3i} and K_i are taken on attaining the system requirement. These parameters are experimentally limited. The computational difficulty can be notably reduced by these boundaries. The limitation of the parameters is tabulated in Table 4.

Table 4. CPSS boundaries

Generator	T_{1i}	T_{2i}
Minimum	0.06	0.06
Maximum	1.0	1.0

IV. IMPERIAL COMPETITIVE ALGORITHM

Imperial Competitive Algorithm (ICA) is one of the population-based optimization algorithms which is inspired by the idea of the evolution in humans' political-social processes. The algorithm is based on prior performance information (colony and imperialist countries) and the assimilation trajectory parameters (absorption) are adjusted through these information. The number of imperialists along with their relevant colonies as a movement of answers, then, does the search operation in the problem area. In this method, each of the possible answers (colonies) tries to converge on the best reached experience (imperialist). Following this process will lead to achieve the optimum point of the objective function via an intelligent search.

In order to better understanding, it tries to be established a relation between GA and ICA algorithms. There are some individuals in the GA algorithm, which form a population. Individuals of the population move in the search space to find the best answer through the influence of composition and mutation operators. The selection of parents as well as new children for the next generation in GA algorithm is based on the fitness of each person [44, 45]. In the ICA algorithm instead of individuals, some countries have the same characteristics as an individual in the GA algorithm that specifies its location in the search space. In this set of countries, which are points of the search space, some of countries, which have more fitness, are elected as imperialist.

In this algorithm, the term of fitness is replaced with the term of power. Hence, the powerful and weak countries are characterized as imperialist and colony respectively. The more powerful an imperialist is, the more colonies it will allocate to itself. At the beginning of the algorithm, countries are randomly generated and some powerful countries selected as imperialists. The other countries are randomly assigned to one of the imperialists whose the number of colonies would be proportional to their power. After dividing all colonies among imperialists, these colonies start moving toward their relevant imperialist. For instance, if an imperialist and colony country are show with a star and circle respectively, movement of the colony toward its relevant imperialist illustrated in Figure 4 [44].

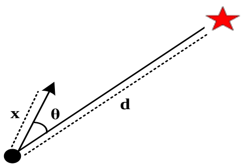

Figure 4. Moving colonies toward their relevant imperialist

Considering a function *f* (*x*) in optimization problems, it tries to find an argument *x* whose relevant cost is optimum (usually minimum). In a N_{var}-dimensional optimization problem, a country is an $N_{var}\times 1$ array. This array is defined as follow:

$$country = \left[P_1, P_2, P_3, ..., P_{N_{var}}\right] \tag{6}$$

In order to start the optimization procedure, the initial population of size '$N_{countery}$' and 'N_{imp}' of the most powerful countries with the lowest cost function according to Equation (3) are elected as imperialists.

$$\cos t_i = f(country_i) = f(P_1, P_2, P_3, ..., P_{N_{var}}) \tag{7}$$

The remaining 'N_{col}' of countries constitute colonies, which each of them belong to an empire. According to imperialist's power, these colonies move toward their pertinent imperialist in accord with Equation (4).

$$\begin{aligned} T.C_n &= cost(imperialist_n) + \\ &+\xi \times \mathrm{mean}\{\cos t(colonies\ of\ empire_n)\} \end{aligned} \tag{8}$$

The total power of an empire is determined by calculating both the power of the imperialist country (the first part of the Equation (4)) plus ζ percentage of the average power of its colonies. As seen in Figure 6, if the distance between colony and imperialist is *d*, the colony moves toward the imperialist by *x* units whose movement is the vector from colony to imperialist. In addition, this movement is deflected by an angle θ which *x* and θ are random variables. The value of θ and *x* uniformly varies in the range of [-γ, γ] and [0, $\beta\times d$] respectively. Where β is a number greater than 1 and γ is the deviation parameter. A value of about 2 for β and about π/4 rad for γ has been suggested to achieve better convergence [44].

If during the imperialistic competition a colony country acquires more power than its pertinent imperialist, the possessions of colony and imperialist will be changed together. In other words, in the later stages of the algorithm, all the countries of the former imperialist will belong to the new imperialist and their movement will be toward it. There is an imperialistic competition among the empires in each iteration of the algorithm. In this competition, any empire that has less power than others will loss one of its colonies. If an empire has no colonies due to the loss of its colonies, it will become as a colony for other imperialist. This process goes on until all the colonies converge to a state in which there is just one empire. In this case, all the colonies will be under control of this empire, and the algorithm will be finished. The flowchart of proposed algorithm is illustrated in Figure 5.

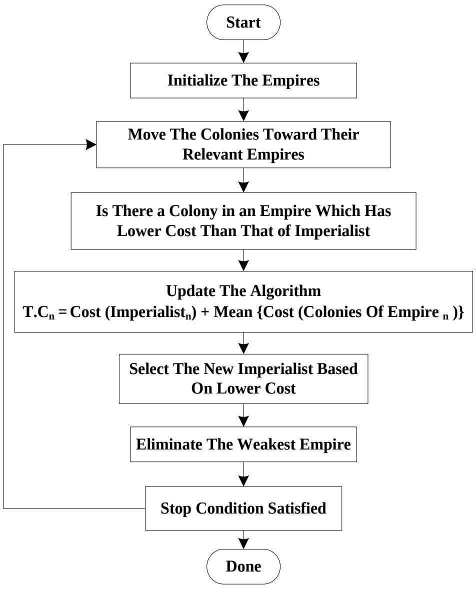

Figure 5. ICA flowchart

V. SIMULATION RESULTS

A. Determination of Crossover and Mutation Probabilities for ICA Algorithm

Crossover and mutation probabilities used at above process affect the final solution of the ICA problem. In this subsection, effect of these probabilities on average fitness function is investigated and optimum values are selected for them. To do so, for a colony size of 100 (N_c = 100), the crossover and mutation probabilities are increased from 0.1 to 0.9 in steps of 0.1 respectively. Then, for every couple of the crossover and mutation probabilities, 10 independent trials are made with the solution of the ICA problem each with 100 iterations and average fitness function among 10 trials is determined. The optimum values for the two probabilities are those giving minimum average fitness function are selected as, crossover probability = 0.3 and mutation probability = 0.7. The other parameters of ICA are replaced as N_{imp} = 3, $V_{\max}$ = 1.05 pu, $V_{\min}$ = 0.95 pu.

B. Experimental Result

The minimum fitness value evaluating process is depicted in Figure 6. As it can be seen from the figure, the convergence of ICA is faster than BFA and GA. This is because ICA algorithm provides the correct answers with high accuracy in the initial iterations, which makes the responding time of loading conditions is this algorithm extremely fast.

The system proper values and damping ratio of mechanical mode with three different loading conditions is tabulated in Table 5. It is clear from the table that the system with ICATCSC is suffered from small damping factors (σ = 0.83, -0.72, -0.59) for light, normal, and heavy loading, respectively.

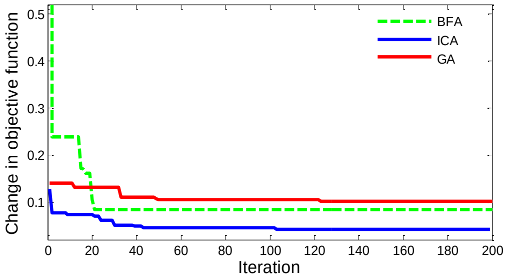

Figure 6. Convergence profile for ICA, BFA and GA

The proposed coordinated controller shifts significantly the electromechanical mode eigenvalues to the left of the S-plane, and consequently the values of the damping factors are considerably enhanced to (σ = -1.21, -1.64, -1.13) for light, normal, and heavy loading respectively. Additionally, the damping ratios commensurate with coordinated controller are almost bigger than the uncoordinated ones. Therefore, the proposed coordinated controller substantially improves the damping features of electromechanical modes and system stability. Table 6 shows of tuned parameters values of different controllers based on the time domain fitness function via proposed ICA technique.

Table 5. Mechanical modes and under different loading condition

Load	ICATCSC	ICAPSS	Coordinated	Uncoordinated
Light	$-3.52 \pm j8.69$, 0.3754	$-2.95 \pm j7.50$, 0.3660	$-5.98 \pm j7.4$, 0.6285	$-4.91 \pm j6.33$, 0.6129
	$-1.98 \pm j5.97$, 0.3147	$-2.96 \pm j6.46$, 0.4165	-5.13 ± 6.63, 0.6119	$-3.23 \pm j7.35$, 0.4023
	$-0.83 \pm j0.63$, 0.7965	$-0.89 \pm j0.89$, 07071	$-1.21 \pm j0.83$, 0.8246	$-091 \pm j0.72$, 0.7842
Normal	$-3.61 \pm j9.93$, 0.3416	$-4.21 \pm j6.20$, 05617	$-8.10 \pm j7.96$, 0.7132	$-3.78 \pm j7.31$, 0.4593
	$-.64 \pm j0.89$, 0.5838	$-3.01 \pm j5.60$, 0.4734	$-6.31 \pm j5.97$, 0.7264	$-2.01 \pm j4.34$, 0.4202
	$-0.72 \pm j0.73$, 0.7022	$-0.83 \pm j0.73$, 0.7511	$-1.64 \pm j0.95$, 0.8653	$-0.60 \pm j0.65$, 0.6782
Heavy	$-4.10 \pm j10$, 0.3793	$-2.31 \pm j4.98$, 0.4207	$-4.93 \pm j8.34$, 0.5088	$-3.18 \pm j6.95$, 0.4160
	$-1.98 \pm j5.81$, 0.3225	$-2.69 \pm j6.31$, 0.3921	$-5.81 \pm j6.64$, 0.6585	$-1.98 \pm j6.00$, 0.3133
	$-0.59 \pm j0.83$, 0.5793	$-1.07 \pm j0.63$, 0.8617	$-1.13 \pm j0.69$, 0.8534	$-0.98 \pm j0.7$, 0.8137

Table 6. Optimal PSSs and TCSCs parameters using different techniques

Parameter	Coordinated Design				Uncoordinated Design			
	PSS1	PSS2	PSS3	TCSC	PSS1	PSS2	PSS3	TCSC
K	23.0121	17.3163	4.3215	1.1203	26.1422	12.9856	7.1205	1.3760
T_1	0.3601	0.1975	0.1145	0.9134	0.2513	0.5142	0.6014	0.4986
T_3	0.0694	0.5974	0.6498	0.1789	0.2541	0.1799	0.3649	0.1387

C. Light Load Condition

The vigorous performance of the proposed coordinated controller under severe disturbance is confirmed by implementing a three-phase fault of 6-cycle duration at 1.0 s close to bus 7. The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$, and $\Delta\omega_{13}$ owing to serious disturbance for light loading condition is depicted in Figures 7 to 9. The ability of the proposed coordinated controller for diminishing the settling time and damping power system oscillations are verified in these figures.

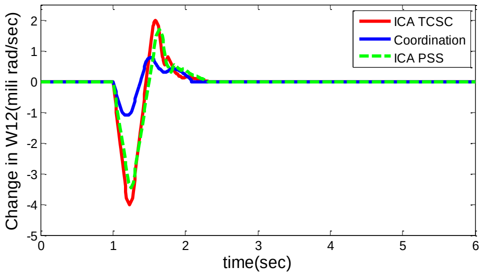

Figure 7. Response of $\Delta\omega_{12}$ for light load condition

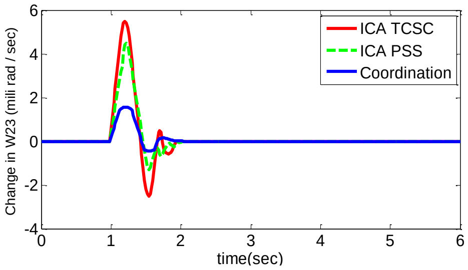

Figure 8. Response of $\Delta\omega_{23}$ for light load condition

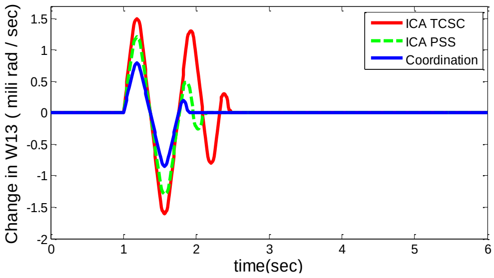

Figure 9. Response of $\Delta\omega_{13}$ for light load condition

In addition, the settling time of these oscillations is T_s = 1.94, 1.99, and 2.04 s for coordinated controller, ICAPSS, and ICATCSC, respectively, and consequently the proposed coordinated controller is able to provide significant damping to the system oscillatory modes in comparison with ICAPSS, and ICATCSC. Additionally, Figure 10 illustrates the response of $\Delta\omega_{12}$ for different optimization scheme. As it can be seen from this figure, ICA reveals better performance so as to design the coordinated controller compared with BFOA and GA.

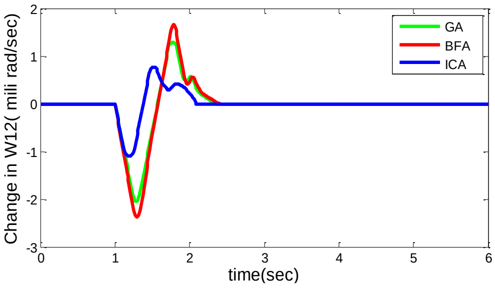

Figure 10. Response of $\Delta\omega_{12}$ for different optimization techniques

D. Normal Load Condition

The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$ and $\Delta\omega_{13}$ owing to same disturbance for normal loading condition is illustrated in Figures 11 to 13. The obtained results reveal that the proposed coordinated controller has a superior ability for damping power system oscillations and intensifies substantially the dynamic stability of the power system. In addition, the settling time of these oscillations is T_s = 1.89, 2.26, and 2.22s for ICAPSS and ICATCSC respectively and consequently the designed controller is competent to provide significant damping to the system oscillatory modes. Therefore, the proposed coordinated controller enlarges the power system stability constrain. Figure 14 depicts a comparison analysis between different schemes. The more competent and speedy convergence can be seen by proposed ICA scheme compared with BFOA and GA.

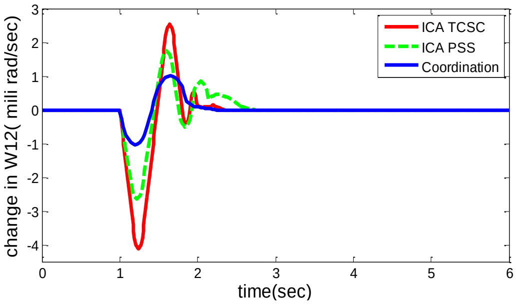

Figure 11. Response of $\Delta\omega_{12}$ for normal load condition

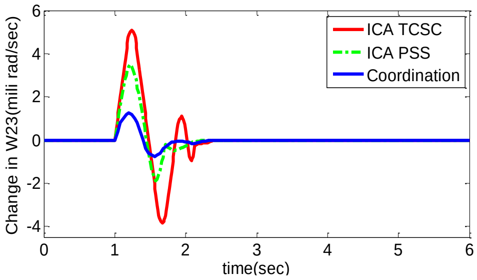

Figure 12. Response of $\Delta\omega_{23}$ for normal load condition

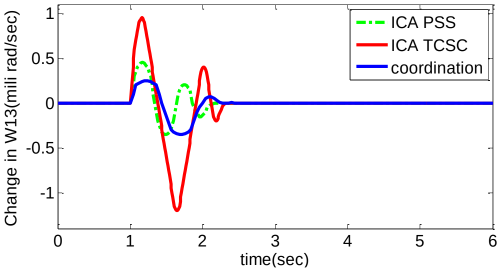

Figure 13. Response of $\Delta\omega_{13}$ for normal load condition

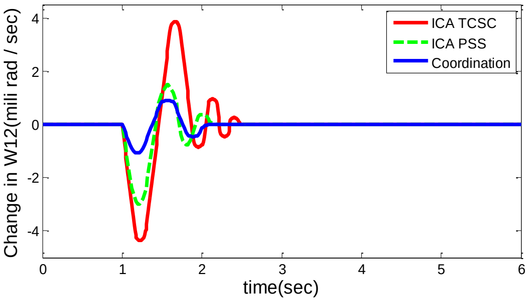

Figure 14. Response of $\Delta\omega_{12}$ for different optimization techniques

E. Heavy Load Condition

The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$ and $\Delta\omega_{13}$ owing to same disturbance for heavy loading condition is illustrated in Figure 15 to 17. As it can be observed from these figures, the proposed coordinated controller reveals better damping features to low frequency oscillations. Furthermore, the settling time of these oscillations is T_s = 1.94, 2.02, and 2.43 s for coordinated controller, ICAPSS and ICATCSC respectively. Therefore, the supremacy of simultaneous coordinated designing of the ICATCSC and ICAPSS is demonstrated to uncoordinated designed controller ones.

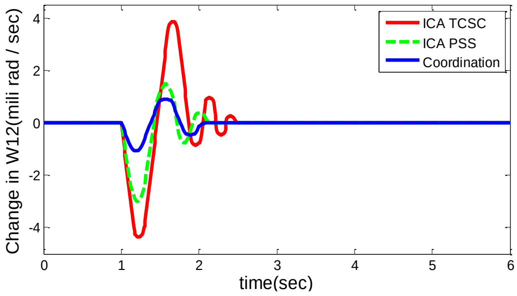

Figure 15. Response of $\Delta\omega_{12}$ for heavy load condition

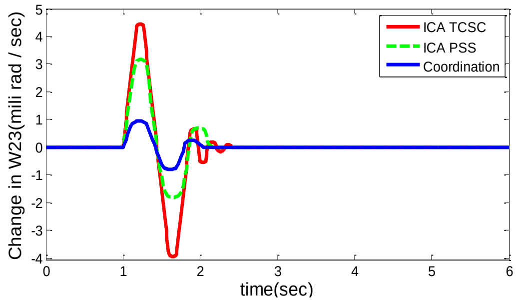

Figure 16. Response of $\Delta\omega_{23}$ for heavy load condition

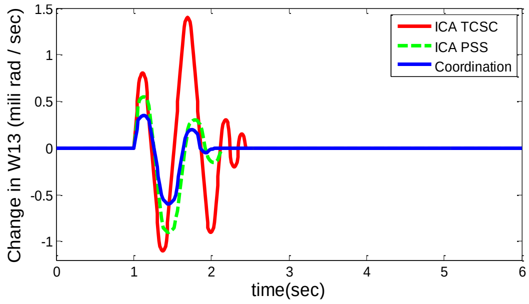

Figure 17. Response of $\Delta\omega_{13}$ for heavy load condition

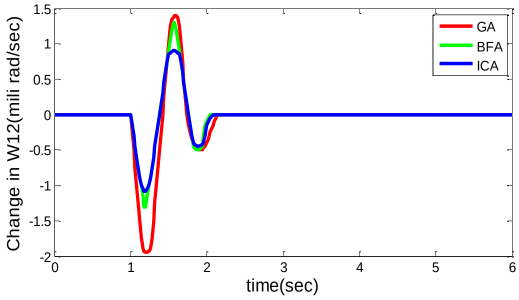

Figure 18. Response of $\Delta\omega_{12}$ for different optimization techniques

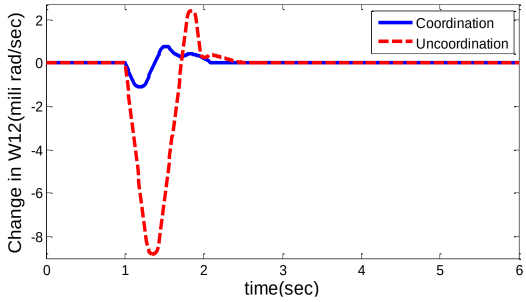

Figure 19. Comparison between coordinated and uncoordinated design

One of the main advantages of this controller is the straightforward structure and potentiality of implementation in real time environment. The supremacy of proposed ICA in adjusting the coordinated controller in comparison with BFOA and GA is shown in Figure 18. Additionally, Figure 19 depicts the coordinated and uncoordinated controller in response of $\Delta\omega_{12}$. Supremacy of proposed coordinated controller in diminishing settling time and damping power system oscillations compared with uncoordinated one illustrates in this figures.

VI. CONCLUSIONS

The subsequent adjusting of PSS and TCSC parameters does not undertake the effectiveness of the PSS and TCSC with variable load condition and location. For this purpose, in this paper, a vigorous design technique for the simultaneous coordinated adjusting of the TCSC and PSS damping controller in a multi-machine power system is represented. The PSSs and TCSC parameters designing problem is converted to an optimization problem in which the speed deviations between generators are associated.

The effectiveness of the proposed scheme is applied on a multi-machine power system for a wide range of loading conditions and disturbances. The obtained results are compared with GA and BFOA based tuned PSS and TCSC to demonstrate its robust ability. The proposed ICA scheme for tuning TCSC and PSSs is easy to implement without additional computational complexity. The ability to jump out the local optima, the convergence accuracy, and speed are notably improved and therefore the high accuracy and competence are achieved.

REFERENCES

[1] Y.N. Yu, "Electric Power System Dynamics", New York Academic Press, 1983.

[2] P.W. Sauer, M.A. Pai, "Power System Dynamics and Stability", Prentice-Hall, Englewood Cliffs, NJ, 1998.

[3] T.C. Yang, "Applying H_1 Optimization Method to Power System Stabilizer Design Parts 1 and 2", Int. Jour. Elec. Power Energy Sys., Vol. 19, No. 1, pp. 29-43, 1997.

[4] R. Asgharian, "A Robust H_1 Power System Stabilizer with no Adverse Effect on Shaft Torsional Modes", IEEE Trans. on Energy Conversion, Vol. 9, No. 3, pp. 475-481, 1994.

[5] M. Vidyasagar, H. Kimura, "Robust Controllers for Uncertain Linear Multivariable Systems", Automatica, Vol. 22, No. 1, pp. 85-94, 1986.

[6] H. Kwakernaak, "Robust Control and H1 Optimization Tutorial", Automatica, Vol. 29, No. 2, pp. 255-273, 1993.

[7] P. Kundur, M. Klein, G.J. Rogers, MS. Zywno, "Application of Power System Stabilizers for Enhancement of Overall System Stability", IEEE Trans. on Power Sys., Vol. 4, No. 2, pp. 614-626, 1989.

[8] Y.L. Abdel-Magid, M.A. Abido, S. Al-Baiyat, A.H. Mantawy, "Simultaneous Stabilization of Multi-Machine Stabilizers via Genetic Algorithm", IEEE Trans. on Power Sys., Vol. 14, No. 4, pp. 1428-1439, 1999.

[9] K. Sebaa, M. Boudour, "Optimal Locations and Tuning of Robust Power System Stabilizer Using Genetic Algorithms", Int. Jour. Electric Power Sys. Res., Vol. 79, No. 2, pp. 406-416, 2009.
[10] Y.L. Abdel-Magid, M.A. Abido, A.H. Mantawy, "Robust Tuning of Power System Stabilizers in Multi-Machine Power Systems", IEEE Trans. on Power Sys., Vol. 15, No. 2, pp. 735-740, 2000.
[11] M.A. Abido, "Robust Design of Multi-Machine Power System Stabilizers Using Simulated Annealing", IEEE Trans. on Energy Conversion, Vol. 15, No. 3, pp. 297-304, 2000.
[12] S. Panda, N.P. Padhy, "Robust Power System Stabilizer Design Using Particle Swarm Optimization Technique", Int. Jour. Elec. Sys. Sci. Eng., Vol. 1, No. 1, pp. 1-8, 2008.
[13] S. Panda, C. Ardil, "Robust Coordinated Design of Multiple Power System Stabilizers Using Particle Swarm Optimization Technique", Int. Jour. Elec. Sys. Sci. Eng., Vol. 1, No. 1, pp. 41-48, 2008.
[14] H. Shayeghi, H.A. Shayanfar, A. Safari, R. Aghmasheh, "A Robust PSSs Design Using PSO in a Multi-Machine Environment", Int. Jour. Energy Converse Manage., Vol. 21, No. 4, pp. 696-702, 2010.
[15] S. Mishra, M. Tripathy, J. Nanda, "Multi-Machine Power System Stabilizer Design by Rule Based Bacteria Foraging", Int. Jour. Electric Power Sys. Res., Vol. 77, No. 12, pp. 1592-1607, 2007.
[16] N.G. Hingorani, L. Gyugyi, "Understanding FACTS - Concepts and Technology of Flexible AC Transmission Systems", IEEE Press, New York, 2000.
[17] B.H. Li, Q.H. Wu, D.R. Turner, P.Y. Wang, X. Zhou, "Modeling of TCSC Dynamics for Control and Analysis of Power System Stability", Int. Jour. Elec. Power Energy Sys., Vol. 22, No. 1, pp. 43-49, 2000.
[18] L. Fan, A. Feliachi, K. Schoder, "Selection and Design of a TCSC Control Signal in Damping Power System Inter-Area Oscillations for Multiple Operating Conditions", Int. Jour. Elec. Power Energy Sys., Vol. 62, No. 2, pp. 127-137, 2002.
[19] A.D. Del Rosso, C.A. Canizares, V.M. Dona, "A Study of TCSC Controller Design for Power System Stability Improvement", IEEE Trans. on Power Sys., Vol. 18, No. 4, pp. 1487-1496, 2003.
[20] J.J.S. Gasca, J.H. Chow, "Power System Reduction to Simplify the Design of Damping Controllers for Inter-Area Oscillations", IEEE Trans. on Power Sys., Vol. 11, No. 3, pp. 1432-1439, 1996.
[21] S. Panda, N.P. Padhy, "Matlab/Simulink Based Model of Single Machine Infinite-Bus with TCSC for Stability Studies and Tuning Employing GA", Int. Jour. Computer Sci. Eng., Vol. 1, No. 1, pp. 50-59 2007.
[22] S. Panda, C. Ardil, S.C. Swain, A.K. Baliarsingh, "Optimal Supplementary Damping Controller Design for TCSC Employing RCGA", Int. Jour. Computer Intell., Vol. 5, No. 1, pp. 36-45, 2009.
[23] M.A. Khaburi, M.R. Haghifam, "A Probabilistic Modeling Based Approach for Total Transfer Capability Enhancement Using FACTS Devices", Int. Jour. Elec. Power Energy Sys., Vol. 32, No. 1, pp. 12-16, 2010.
[24] S. Hameed, B. Das, V. Pant", Reduced Rule Base Self Tuning Fuzzy PI Controller for TCSC", Int. Jour. Elec. Power Energy Sys., Vol. 32, No. 9, pp. 1005-1013, 2010.
[25] L. Khan, I. Ullah, T. Saeed, K.L. Lo, "Virtual Bees Algorithm Based Design of Damping Control System for TCSC", Aust. Jour. Basic Appl. Sci., Vol. 4, No. 1, pp. 1-18, 2010.
[26] M.S. Kumar, P. Renuga, "Bacterial Foraging Algorithm Based Enhancement of Voltage Profile and Minimization of Losses Using TCSC", Int. Jour. Computer Appl., Vol. 7, No. 2, pp. 21-27, 2010.
[27] S. Panda, "Multi-Objective PID Controller Tuning for a FACTS Based Damping Stabilizer Using Non-Dominated Sorting Genetic Algorithm-II", Int. Jour. Elec. Power Energy Sys., Vol. 33, No. 7, pp. 1296-1308, 2011.
[28] Y.L. Abdel-Magid, M.A. Abido, "Robust Coordination Design of Excitation and TCSC Based Stabilizer Using Genetic Algorithms", Int. Jour. Electric Power Sys. Res., Vol. 69, No. 2-4, pp. 129-141, 2004.
[29] M.A. Abido, "Pole Placement Technique for PSS and TCSC Based Stabilizer Design Using Simulated Annealing", Int. Jour. Electric Power Energy Sys., Vol. 22, No. 8, pp. 543-554, 2000.
[30] S. Panda, N.P. Padhy, "Power System with PSS and FACTS Controller - Modeling, Simulation, and Simultaneous Tuning Employing GA", Int. Jour. Elec. Computer Sys. Eng., Vol. 1, No. 1, pp. 9-18, 2007.
[31] S. Panda, N.P. Padhy, "Coordinated Design of TCSC Controller and PSS Employing Particle Swarm Optimization Technique", Int. Jour. Computer Inform. Sci. Eng., Vol. 1, No. 1, pp. 1-9, 2007.
[32] M.I. Alomoush, "Coordinated Tuning of IPFC and PSS to Improve Power System Stability Using BFO", UPEC, 31st August - 3rd September 2010.
[33] H. Shayeghi, A. Safari, H.A. Shayanfar, "PSS and TCSC Damping Controller Coordinated Design Using PSO in Multi-Machine Power System", Int. Jour. Energy Convers Manage., Vol. 51, No. 12, pp. 2930-2937, 2010.
[34] J. Kennedy, R. Eberhart, "Particle Swarm Optimization", IEEE International Conference on Neural Networks, pp. 1942-1948, 1995.
[35] K.M. Passino, "Bio Mimicry of Bacterial Foraging for Distributed Optimization and Control", IEEE Control Sys. Mag., Vol. 22, No. 3, pp. 52-67, 2002.
[36] S. Falilzadeh, M. Darabian, M. Azari, "Static Var Compensator Controller Design for Improving Power System Stability", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 14, Vol. 5, No. 1, pp. 44-51, March 2013.
[37] D.B. Fogel, "Evolutionary Computation towards a New Philosophy of Machine Intelligence", New York, IEEE, 1995.
[38] E.S. Ali, S.M. Abd-Elazim, "Bacteria Foraging Optimization Algorithm Based Load Frequency Controller for Interconnected Power System", Int. Jour. Elec. Power Energy Sys., Vol. 33, No. 3, pp. 633-638, 2011.

[39] S. Subramanian, S. Padma, "Optimal Design of Single Phase Transformer Using Bacterial Foraging Algorithm", Int. Jour. Eng. Sci. Technol., Vol. 3, No. 4, pp. 2677-2684, 2011.
[40] A. Biswas, S. Dasgupta, S. Das, A. Abraham, "Synergy of PSO and Bacterial Foraging Optimization - A Comparative Study on Numerical Benchmarks", Innovations in Hybrid Intelligent Systems, ASC, Vol. 44, pp. 255-263, 2007.
[41] W. Korani, "Bacterial Foraging Oriented by Particle Swarm Optimization Strategy for PID Tuning", GECCO'08, Atlanta, Georgia, USA, pp. 1823-26, 12-16 July 2008.
[42] P.M. Anderson, A.A. Fouad, "Power System Control and Stability", Iowa State University Press, Iowa, 1977.
[43] M. Ishimaru, R. Yokoyama, G. Shirai, T. Niimura, "Robust Thyristor Controlled Series Capacitor Controller Design Based on Linear Matrix Inequality for a Multi-Machine Power System", Int. Jour. Elec. Power Energy Sys., Vol. 24, No. 8, pp. 621-629, 2002.
[44] A. Gargari, C. Lucas, "Imperialist Competitive Algorithm - An Algorithm for Optimization Inspired by Imperialistic Competition", IEEE Congress on Evolutionary Computation (CEC 2007), pp. 4661-4667, 2007.
[45] A. Jalilvand, M. Azari. "Robust Tuning of PSS Controller Based on Imperialist Competitive Algorithm", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 13, Vol. 4, No. 4, pp. 5-10, December 2012.

BIOGRAPHIES

Bahram Khorram received the B.Sc. degree in Electrical Engineering from Abhar Branch, Islamic Azad University, Abhar, Iran, in 2008. He is currently the M.Sc. student at Department of Power Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran. His research interests include application of IEC standards and intelligent methods in, power system dynamics and FACTS devices.

Hamid Lesani received the M.Sc. degree in Electrical Power Engineering from University of Tehran, Tehran, Iran, in 1975, and the Ph.D. degree in Electrical Engineering from Dundee University, UK, in 1987. He is currently Professor in Department of Electrical and Computer Engineering, University of Tehran. His teaching and research interests include design and modeling of electrical machines and power system dynamics. He is a member of IEEE, and a member of the Control and Intelligent Processing Center of Excellency at the University of Tehran.

Javad Olamaei received the B.Sc., M.Sc. and Ph.D. degrees in Electrical Engineering from the University of Tabriz, Tabriz, Iran and Amirkabir University of Technology, Tehran, Iran and Science and Research Branch, Islamic Azad University Tehran, Iran, in 1988, 1992 and 2007, respectively. He is now an Assistant Professor in Department of Electrical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran. His research interests include power distribution system, distributed generation, and reactive power control. He is a member of the Institute of Electrical and Electronics Engineers (IEEE).