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STABILITY ENHANCEMENT OF A POWER SYSTEM WITH A TCSC BASED DAMPING CONTROLLER USING ICA

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Abstract- Suppress of oscillations in power system is an important research issue. This paper deals with a robust controller design using the Imperialist Competitive Algorithm (ICA) optimization technique for Thyristor Controlled Series Compensation (TCSC) to improve the damping of oscillations in power systems. The design problem of TCSC based stabilizer is formulated as an optimization problem where the ICA algorithm is applied to search for the optimal setting of the stabilizer parameter. To ensure the robustness of the proposed stabilizers, the design process takes a wide range of operating conditions into account. Moreover, the results are compared to the results obtained using the Particle Swarm Optimization (PSO) to show the effectiveness of using ICA to attain a global optimal solution of the proposed design problem.

Keywords: Suppression of Oscillations, Multi-Machine Power System, TCSC, Imperialist Competitive Algorithm.

I. INTRODUCTION

A problem of interest in the power industry is the suppression of power system oscillations. These oscillations are related to the dynamics of system power transfer and often exhibit poor damping. With utilities increasing power exchanges over a fixed network, application of new and existing equipment in transmission system for damping these oscillations is being considered [1]. With the advent of Flexible AC Transmission System (FACTS) technology, shunt FACTS devices play an important role in controlling the reactive power flow in the power network and hence the system voltage fluctuations, improving power oscillations damping and stability [2-4].

Amongst the available FACTS devices for transient stability enhancement, the TCSC is the most versatile one [5-6]. The TCSC is a series FACTS device, which allows rapid and continuous changes of the transmission line impedance. It can have various roles in the operation and control of power systems, such as scheduling power flow, decreasing unsymmetrical components, reducing net loss, providing voltage support, limiting short-circuit currents, mitigating sub-synchronous resonance, damping the power oscillation, and enhancing transient stability [7, 8].

Even though the primary purpose of TCSC is to control power flow and increase loading capacity of transmission lines, it is also capable of improving the power system stability. When a TCSC is present in a power system to control the power flow, a supplementary damping controller could be designed to modulate the TCSC reactance during small disturbances in order to improve damping of system oscillations [9, 10]. In recent years, many researchers have posed methods for designing TCSC to enhance the damping of electromechanical oscillations of power systems and application of different optimization techniques in improving power system stability.

The power system stability enhancement via Power System Stabilizer (PSS) and TCSC based stabilizer when applied independently and through coordinated application is discussed and investigated in [11]. Proposed an oscillation transient energy function descent strategy for designing the fuzzy TCSC damping controller [12]. In this study, the TCSC controller actually consists of two TCSC fuzzy controllers and the efficacy of the developed controller has been tested on a four-generator, two-area interconnected power system. The damping control strategy employs non-optimal fuzzy logic controllers in which the system's response settling time is unbearable.

Moreover, the initial parameters adjustment of this type of controller needs some trial and error procedure. It also has been used a self-tuning fuzzy PI control for the TCSC to enhance power system damping and stability[13]. Although, the fuzzy PI controller is simpler and more applicable to remove the steady state error, it is known to give poor performance in the system transient response. It also is used a fuzzy damping controller designed by micro GA technique for the UPFC and TCSC to improve powers system low frequency oscillations [14].

The proposed method may not have enough robustness due to its simplicity against the different kinds of uncertainties and disturbances. In reality, researchers used many approach for optimal designing of TCSC for different application in power system. This paper proposes optimization algorithm as Imperialist Competitive Algorithm (ICA) for optimal designing of damping controller for TCSC in a multi-machine power system to deduct power system oscillations.

The design problem of the proposed controller is formulated as an optimization problem and ICA is employed to search for optimal controller parameters [15-16]. Simulations results shows the effectiveness of the proposed controller in providing good damping characteristic to system oscillations over a wide range of loading conditions. For validate the superiority of the ICA method in tuning controller, results of ICA compared with PSO method.

II. POWER SYSTEM MODEL

The nonlinear model of power system is described as a set of differential equations are as follow:

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

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

The linearized incremental models around an equilibrium point are usually exploited for design of TCSC. Therefore, the state equation of a power system with m TCSC and n machines explained as:

$$A = \frac{\partial f}{\partial X}, \quad B = \frac{\partial f}{\partial U} \tag{2}$$

where, X is a $5n\times1$ state vector and U is an $m\times1$ input vector, A is a $5n\times5n$ matrix and B is a $5n\times m$ matrix. Both A and B are evaluated at a certain operating point.

Figure 1 shows the single line diagram of the system under study. Details of the system data are given in [17]. Participation matrix can be used in mode identification. The frequencies and eigenvalues associated with the rotor oscillation modes of the system shown in Table 1. For example, Table 1 shows that the 0.2371 Hz mode is the inter area mode with G_1 swinging against G_2 and G_3. The 1.2955 Hz frequencies mode is inter-machine oscillation local to G_2. Therefore, 1.8493 Hz frequencies mode is the inter-machine mode local to G_3. The system instability indicates by the positive real part of eigenvalue of G_1. The proper values and frequencies connected to the rotor oscillation modes of system are tabulated in Table 1.

III. DAMPING CONTROLLER DESIGN AND TCSC MODELING

The Thyristor Controlled Reactor (TCR) is formed by a reactor in series with a bi-directional thyristor valve, which is fired by a phase angle α in $90^\circ \le \alpha \le 180^\circ$ ranging with respect to the capacitor voltage. A TCSC can be modeled as a variable reactance, for the dynamic stability analysis and load flow studies. The dynamic equation of TCSC reactance can be expressed as following:

$$\Delta \dot{X}_{TCSC} = (K_S(\Delta X^{ref}_{TCSC} + \Delta U_{TCSC}) - \Delta X_{TCSC}) / T_S \tag{3}$$

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

The TCSC structure used in this study is depicted in Figure 2. In this paper, the parameters of the damping controllers are obtained using the ICA algorithm.

Table 1. The eigenvalues and frequencies associated with the rotor oscillation modes of the case study system

Generator	Eigenvalues	Frequencies	Damping ratio ζ
G_1	+0.15 ± 1.49j	0.2371	-0.1002
G_2	-0.35 ± 8.14j	1.2955	0.0430
G_3	-0.67 ± 11.62j	1.8493	0.0576

Table 2. Loading condition for the system

Generator	Light		Normal		Heavy	
	P	Q	P	Q	P	Q
G_1	0.9649	0.223	1.7164	0.6205	3.5730	1.8143
G_2	1.0000	-0.1933	1.630	0.0665	2.20	0.7127
G_3	0.4500	-0.2668	0.85	0.1086	1.35	0.4313
Load						
A	0.70	0.350	1.25	0.5	2.00	0.90
B	0.50	0.30	0.9	0.30	1.80	0.60
C	0.600	0.200	1.00	0.35	1.60	0.65
Local load	0.600	0.200	1.000	0.35	1.60	0.65

Table 3. Line flow data on 100 MVA base for the case study system

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

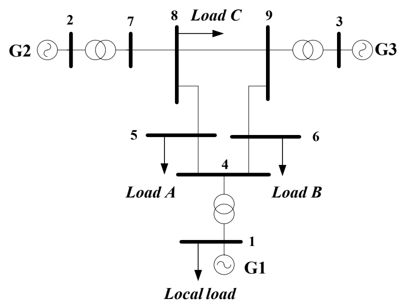

Figure 1. Case study system

Numerous input signals have been proposed for the FACTS to damp the system oscillations. To be possible signals, which carry invaluable information about the inter-area mode, considered as input signals. FACTS controllers are located in transmission systems, for this reason, local input signals are always preferred. Proposed transmission line active power has been as an effective input signal for series FACTS devices damping controller design [18]. Here, the active power of the transmission line is selected as the input signal.

Table 3 gives the line flow data. In the system under study, the power flow in line 5-7 is the largest power flow and this line is the longest line in the system. So, one will consider this line as the best location for installing the TCSC controller in this system. Therefore, this line selected for installing the TCSC in this paper.

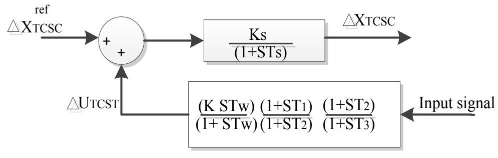

Figure 2. Block diagram of TCSC

IV. OBJECTIVE FUNCTION

After a disturbance, to provide greater damping and maintain stability, the parameters of the TCSC may be selected to minimize the following objective function [20]:

$$J=\sum_{j=1}^{n_p}\sum_{\sigma_{ij}\geq\sigma_0}[\sigma_0-\sigma_{ij}]^2+a\sum_{j=1}^{n_p}\sum_{\xi_{ij}\geq\xi_0}[\xi_0-\xi_{ij}]^2 \quad (4)$$

The system closed loop eigenvalues in the D-shape sector characterized by $\sigma_{ij} \leq \sigma_0$ and $\zeta_{ij} > \zeta_0$ is depicted in Figure 3. Where, n_p is the number of operating points considered in the design process, σ and ζ are the real part and the damping ratio of the eigenvalue of the operating point (In this study, σ_0= -0.5 and ζ_0 = 0.10).

In this study, to reduce the computational burden, the value of the wash out time constant T_W is fixed to 10s, and tuning of T_1-T_4 are undertaken to achieve the net phase lead required by the system. Typical ranges of optimized parameters for K and T_1 to T_4 are [0.01-50] and [0.01-1.0] respectively. In fact, objective function J_t optimization problem is minimize J_t with observes below constraints:

$$\begin{cases} K^{\min} \leq K \leq^{\max} \\ T_1^{\min} \leq T_1 \leq T_2^{\max} \\ \mathrm{T}_2^{\min} \leq T_2 \leq T_2^{\max} \\ T_3^{\min} \leq T_3 \leq T_3^{\max} \\ T_4^{\min} \leq T_4 \leq T_4^{\max} \end{cases} \quad (5)$$

The proposed design is optimized through ICA algorithm to search the optimal set of TCSC controller parameters to reach these goals, improving the damping characteristics and also obtaining a good performance under all operating conditions and various loads and finally designing a low order controller for easy execution.

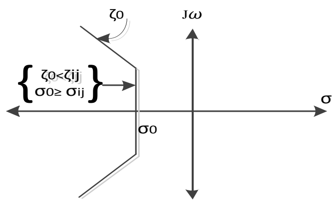

Figure 3. D-shape sector in the s-plane

V. IMPERIALIST COMPETITIVE ALGORITHM

Imperialist Competitive Algorithm (ICA) is a new global heuristic search that applies imperialism and imperialistic competition process as a source of inspiration, proposed by Atashpaz Gargari and Lucas [21]. ICA uses socio-political evolution of human as a source of inspiration for developing a strong optimization strategy [19]. The pseudo code of this algorithm is demonstrated in the end of this Section.

The ICA starts with an initial population, called countries. Some of the best countries are selected to be the imperialist states and the rest forms are the colonies of these imperialists. All the remained colonies of initial countries are divided among the mentioned imperialists based on their power after dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist country.

This movement is a simple model of assimilation policy, which was pursued by some of the imperialist states. The movement of a colony towards the imperialist is shown Figure 4. The x and θ are arbitrary numbers which are generated uniformly $x \sim U(0, \beta\times d)$, $h \sim U(-\gamma, \gamma)$ and d is the interval between colony and imperialist and β must be greater than one, in this movement. This constraint causes the colonies to get closer to the imperialist state from both sides. Moreover, γ is a parameter that adopts the deviation from the main direction. The β and γ are random numbers, most of the times the best fitted value of β and γ are approximately 2 and π/4 (rad) [21].

The power of the imperialist country in addition to the power of its colonies, determine the total power of an empire. More explicitly, a percentage of the mean power of each imperialist's colonies is added to power of imperialist to form the total power of an empire. Any empire that does not improve in imperialist competition will be diminished. As a result, the imperialistic competition will be growth the power of great empires and weakened the frail ones.

Hence, weak empires will collapse finally. The movement of colonies toward their related imperialists along with competition among empires and collapse mechanism will bring out the countries to converge to a state in which there exist just one empire in the world and all the rests are its colonies. In this final stage colonies have the same position and power as the imperialist [22]. Determining the optimum values of the initial parameter is the most important task in any system modeling approach. Below described pseudo code for the ICA algorithm [21]:

1- Select some random points on the function and start empires.
2- Move the colonies toward their relevant imperialist.
3- Compare costs of colonies and empire, if there is a colony in an empire with lower cost than that of imperialist, swap positions that imperialist of and colony.
4- Calculate the total cost of all empires (Related to the power of both imperialist and its colonies).
5- Choose the weakest colony from the weakest empire and give it to the empire with the most likelihood to possess it (Imperialistic competition).
6- Eliminate the powerless empires.
7- If reach to predefined iterations or there is just one empire, stop, else go to step 2 and continue.

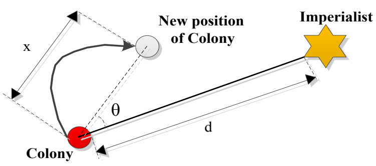

Figure 4. Structure of the proposed FFs model

VI. SIMULATIONS RESULTS

The program for the imperialist competitive based optimization algorithm used in this study has written in MATLAB 2011a. In order to acquire better performance, the parameters selected for the proposed ICA algorithm as shown in Table 4.

Table 4. Parameters of ICA algorithm

Parameters	N_{imp}	x_1	x_2	V_{max}	V_{min}
Value	3	0.85	0.25	1.05	0.95

The variations of objective function with two different optimization methods shown in Figure 5. In both of ICA and PSO techniques the objective functions decrease monotonically and the final value of the objective function is $J_t = 0$, indicating that all modes have been shifted to the specified *D*-shape sector in the *S*-plane and the proposed objective function is satisfied. ICA and PSO converge at 27 and 176 generation respectively, it is clear ICA converges at a faster rate compared to that for PSO.

The system eigenvalues and damping ratio of mechanical mode with three different loading conditions are shown in Table 5. It is clear that the system with open loop is unstable for each three loading conditions. ICATCSC shift substantially the electromechanical mode eigenvalues to the left of the *D*-shape in the S-plane and the value of the damping factor (σ) with the proposed method is significantly improved to -0.65 for light, -0.62 for normal, and 0.85 for heavy loading.

Hence compared to open loop and PSOTCSC, ICATCSC greatly improves the damping characteristics of electromechanical modes and enhances system stability. The results of TCSC parameters set values based on the proposed objective function using ICA, and PSO is shown in Table 6. The next sections discuss and consider to three different loading conditions on the separate parts.

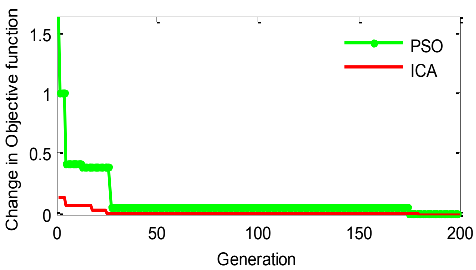

Figure 6. Convergence of objective function with the generations

Table 5. Mechanical modes and ζ under different loading conditions and controllers

Options	No Controller	ICA TCSC	PSO TCSC
Light Load	-0.79±9.83*j*, 0.0801	-3.94±9.02*j*, 0.4116	-3.24±8.91*j*, 0.3485
	-0.58±7.85*j*, 0.0737	-2.06±6.11*j*, 0.3250	-1.91±6.39*j*, 0.2903
	+0.05±0.92*j*, -0.054	-0.65±0.658*j*, 0.7788	-0.51±0.697*j*, 0.6313
Normal Load	-0.58±11.83, 0.04896	-3.21±11.48*j*, 0.2725	-2.96±11.51*j*, 0.2515
	-0.29±8.47*j*, 0.0342	-1.36±6.19*j*, 0.2116	-0.97±6.13*j*, 0.1568
	+0.14±1.79*j*, -0.78	-0.62±0.71*j*, 0.7174	-0.58±0.725*j*, 0.6743
Heavy Load	-0.48±12.15, 0.039	-3.66±11.12*j*, 0.3181	-2.91±11.31*j*, 0.2517
	-0.16±8.73*j*, 0.0183	-0.86±5.43*j*, 0.1569	-0.712±5.86*j*, 0.1208
	+0.052±2.04*j*, -0.025	-0.85±0.738*j*, 0.8553	-0.79±0.831*j*, 0.7597

Table 6. Optimal parameters of the controller

Parameters	PSOTCSC	ICATCSC
T_1	0.4826	0.3966
T_2	0.2604	0.2941
T_3	0.0839	0.0662
T_4	0.1585	0.1279
K	3.693	0.1722

A. Case 1 - Light Load Condition

For verified the effectiveness of the performance of the proposed ICATCSC under severe disturbance, applying a three-phase fault of 6-cycle duration at 1.0 sec near bus 7.

The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$, and $\Delta\omega_{13}$ due to severe disturbance for light loading condition is shown in Figures 6-8. Whit due attention to these figures, it can be seen that the ICA based tuned TCSC using the proposed objective function achieves good robust performance and provides superior damping in comparison with the NC and PSO technique. The required mean time to suppress these oscillations for ICATCSC and PSOTCSC is approximately 2.46 sec and 2.88 sec, respectively. As observation in these figures, for open loop system the oscillations are increased rapidly.

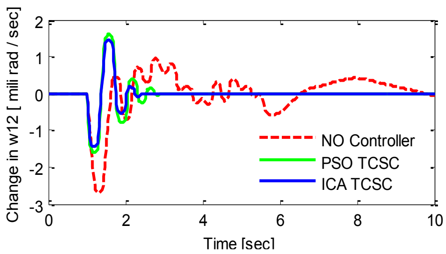

Figure 6. Response of $\Delta\omega_{12}$ for light load condition

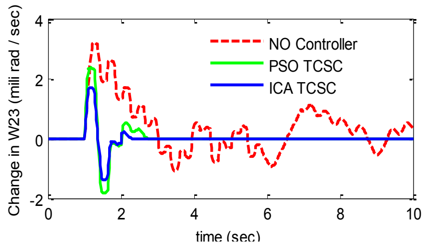

Figure 7. Response of $\Delta\omega_{23}$ for light load condition

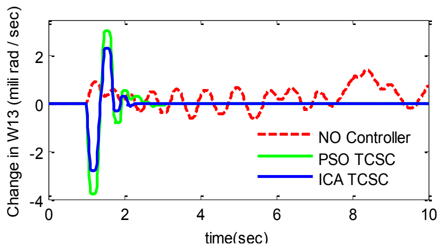

Figure 8. Response of $\Delta\omega_{13}$ for light load condition

B. Case 2 - Normal Load Condition

The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$, and $\Delta\omega_{13}$ due to same disturbance for normal loading condition is shown in Figures 9-11. From these figures, it can be seen that the capability of the ICATCSC in damping power system oscillations and reducing settling time. The mean settling time of these oscillations is 2.48 sec for ICATCSC and 3.24 sec for PSOTCSC. Hence, ICATCSC is capable of providing sufficient damping to system oscillatory modes compared with open loop case and PSOTCSC. In addition, in this loading condition similar to light loading for open loop case the oscillations is increased rapidly and the system is unstable.

C. Case 3 - Heavy Load Condition

The system response at heavy loading condition with fixing controller parameters is shown in Figures 12-14. Whit due attention to these figures, it can be seen that the response with proposed ICATCSC shows good damping characteristics and system is more quickly stabilized than PSOTCSC.

The mean settling time of oscillation is 2.76 sec. for ICATCSC and 3.82 sec for PSOTCSC. In addition, in this loading condition similar to light and normal loading for open loop case the oscillations is increased rapidly and the system is unstable. Hence, the ICATCSC extend the power transfer capability and the power system stability limit.

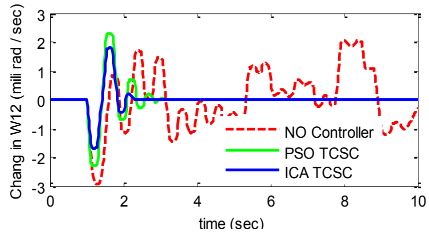

Figure 9. Response of $\Delta\omega_{12}$ for normal load condition

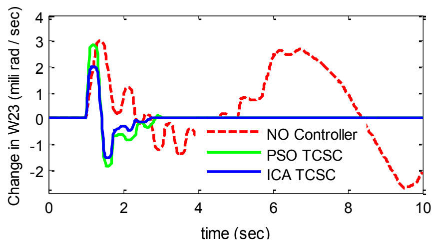

Figure 10. Response of $\Delta\omega_{23}$ for normal load condition

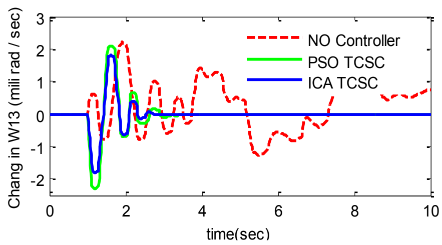

Figure 11. Response of $\Delta\omega_{13}$ for normal load condition

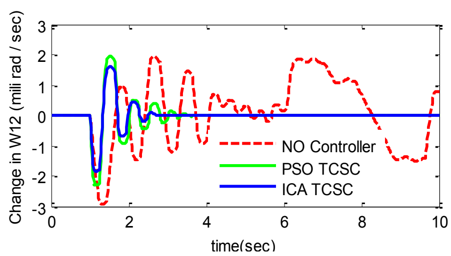

Figure 12. Response of $\Delta\omega_{12}$ for heavy load condition

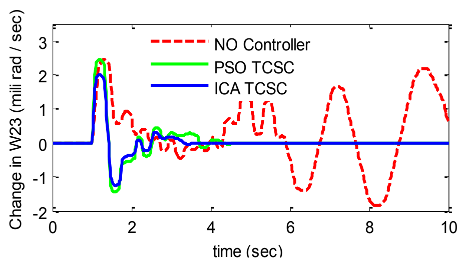

Figure 13. Response of $\Delta\omega_{23}$ for heavy load condition

Table 7. Values of *ITAE* index

Loading Condition	*ITAE*	
	ICA TCSC	PSO TCSC
Light Load	0.0031	0.0036
Normal Load	0.0038	0.0066
Heavy Load	0.0064	0.0121

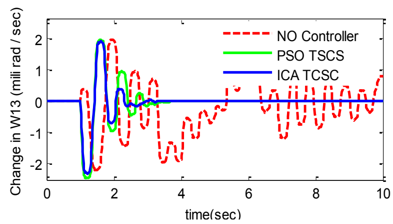

Figure 14. Response of $\Delta\omega_{13}$ for heavy load condition

In end of this section to demonstrate the robustness of the proposed controller, a performance index as:

$$ITAE = \int_{0}^{30} t\left(|\Delta\omega_{12}| + |\Delta\omega_{23}| + |\Delta\omega_{13}|\right) dt \quad (6)$$

where, *ITAE* is the Integral of time multiplied absolute value of the error and $\Delta\omega_{12}=\Delta\omega_1-\Delta\omega_2$, $\Delta\omega_{23}=\Delta\omega_2-\Delta\omega_3$, and $\Delta\omega_{13}=\Delta\omega_1-\Delta\omega_3$. The lower the value of this index is, the better the system response in terms of time domain characteristics.

The numerical results of performance robustness for ICA and PSO methods in three loading condition is shown in Table 7 and Figure 15. It is clear values of these system performance characteristics with ICATCSC are much smaller than PSOTCSC. Moreover, this demonstrates that speed deviations, settling time, undershoot and overshoot of all units are greatly reduced by applying the proposed ICA based tuned TCSC parameters.

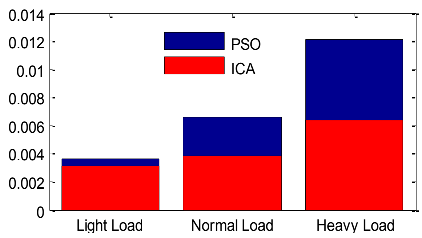

Figure 15. Values of ITAE index

VII. CONCLUSIONS

In this study, Imperialist Competitive Algorithm (ICA) algorithm optimization technique is employed for optimal designing of damping controller for TCSC in a multi-machine power system to suppress power system oscillations and obtaining a good performance under all operating conditions and various loads. For the design problem, an eigenvalue based objective function reflecting the combination of damping factor and damping ratio are defined for different operating conditions and ICA employed to solve the problem.

The effectiveness of the proposed controller has been tested on a three-machine power system through the simulation studies under different operating conditions and the proposed method validated by compared with PSO method optimization.

The performance of the proposed technique is compared with the performance of Genetic Algorithm to reveal its robust performance in tuning TCSC controller. The superiority of proposed scheme in comparison with PSO can be summarized as the following:
- Damping out local as well as inter area modes of oscillations
- The faster convergence and less time consuming
- The less fitness function, which shows its robust preference than other method
- The ability to jump out the local optimal
- Providing the correct answers with high accuracy in the initial iterations
- Superiority in computational simplicity success rate and solution quality

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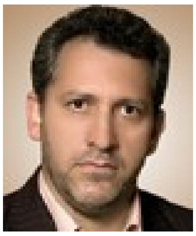

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