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Coordinated Design of Power System Stabilizer Using Thyristor Controlled Series Compensator Controller: An Artificial Bee Colony Approach

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Abstract— **This paper introduces a novel application of artificial bee colony (ABC) in designing the coordinated Power System Stabilizer (PSS) with Thyristor Controlled Series Compensator (TCSC) based Controller to improve the transient stability of single machine connected to infinite bus through transmission line. Various simulation results and comparisons over different loading conditions on a single machine infinite bus power system shows the superiority of ABC in designing the coordinated controller.**

Keywords-component; Artificial Bee Colony, PSS, TCSC, Phillips-heffron model, small signal stability.

I. INTRODUCTION

In the earlier days, the power systems were simple and relatively non-remote. In the recent years the complexity of power system has been drastically increased with the rapid growth of power demand [1]. Due to limited availability of resources and other environmental constraints modern day power systems are getting more loaded than before causing system to operate near their transient stability limits. To meet the rising demand of power, the quantity and reliability of transmitted power should be improved which demands the need for power flow control in complex interconnected electrical power systems [1].

The distantly located interconnected power systems need to be maintained at constant operating voltage for the reason by which Automatic Voltage Regulator (AVR) for synchronous generator comes in to picture. AVR leads to low frequency oscillations (0.1 to 3 Hz) and causes negative damping on the rotor [2]. These oscillations may become large and leads to loss of synchronism by affecting small signal stability [3]. Small signal stability refers to the ability to maintain synchronism under small disturbances, which are generally caused by small variations in loads and generation.

Since 1960’s conventional Lead-lag Power System Stabilizers (PSS) were being used to produce positive damping on generator rotor oscillations by controlling its excitation by providing supplementary control signal. PSS produces a component of electrical torque in the direction of speed deviation, which accounts for positive damping on rotor oscillations [4]. But PSS causes variations in voltage profiles and it’s operating time is relatively high [1].

Due to advancement in Power Electronic Drive technologies, Flexible AC Transmission Systems (FACTS) devices have been economically proved to be very useful for enhancement of power system stability and power transfer capacity, decreasing line losses and generation costs ameliorates security of power system [5-7]. Fundamental feature of Thyristor based switching controllers is that speed of response of passive power system components (C & L) and system mechanical response will get enhanced.

Thyristor Controlled Series Compensator (TCSC) belongs to first generation FACTS devices. It is widely useful because of its effectiveness in solving transient problems and is less expensive. It’s flexibility and quickness in adjusting the reactance of transmission line helps in achieving better utilization of transmission capability, efficient power flow control, transient stability improvement, power oscillation damping & fault current location [8, 9].

To carry the small signal stability studies of Single Machine Infinite Bus (SMIB) linear model of Philip-Heffron, which is well known model for synchronous generators is considered. It is quite accurate for the small signal stability studies of power systems [10]. It has worked successfully for the designing and tuning of conventional power system stabilizers.

The parameter tuning of TCSC controller should be coordinated with PSS to avoid destabilizing interactions [11, 12]. As this is a coordinated control there will be a total of 10 parameters to be tuned for optimal performance, which calls for real parameter optimization. For this approach we applied new swarm intelligent based Artificial Bee Colony algorithm. Karaboga and Basturk proposed artificial Bee Colony algorithm for numerical function optimization [17, 18]. Due its simplicity in structure and also having good

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global and local exploration skills it had been used in designing many real world practical problems. In this application we had used ABC in designing TCSC controller coordinated with PSS.

The rest of paper is organized as follows; Section II deals with the mathematical modeling of power system for single machine. In Section III the problem is formulated followed by the objective function considered. Section IV briefs the Artificial Bee Colony algorithm and design scheme is been provided in Section V. The simulations and results are put forth in Section VI and at end we provide few conclusions.

II. POWER SYSTEM MODELLING

The Single Machine connected to Infinite Bus through transmission line with TCSC controller shown in figure is being considered for small signal stability studies.

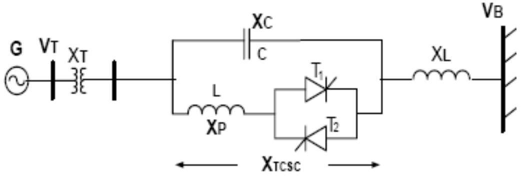

Fig 1: Single machine infinite bus power system with TCSC [3]

A. Generator Modelling

The synchronous machine is described by 4th order model and the Philip-Heffron's model of Single Machine Infinite Bus with TCSC controller is obtained by linearizing system equations around an operating condition of Power system [11].

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{1}$$

$$\Delta\dot{\omega} = [-K_1\Delta\delta - K_2\Delta E_q^{'} - K_p\Delta\sigma - D\Delta\omega]/M \tag{2}$$

$$\Delta\dot{E}_q^{'} = [-K_4\Delta\delta - K_3\Delta E_q^{'} - K_q\Delta\sigma + \Delta E_{fd}]/T_{do}^{'} \tag{3}$$

$$\Delta\dot{E}_{fd} = [-K_A(K_5\Delta\delta + K_6\Delta E_q^{'} + K_v\Delta\sigma) - \Delta E_{fd}]/T_A \tag{4}$$

$$\begin{gathered} K_1 = \partial P_e/\partial\delta, K_2 = \partial P_e/\partial E_q^{'}, K_p = \partial P_e/\partial\sigma \\ K_4 = \partial E_q/\partial\delta, K_3 = \partial E_q/\partial E_q^{'}, K_q = \partial E_q/\partial\sigma \\ K_5 = \partial V_T/\partial\delta, K_6 = \partial V_T/\partial E_q{'}, K_v = \partial V_T/\partial\sigma \end{gathered} \tag{5}$$

The system has a TCSC controller installed in the transmission line. In the figure X_T and X_L represent the reactance of the transformer and the transmission line respectively. V_T and V_B are the generator terminal voltage and infinite bus voltage respectively.

B. PSS and Excitation system

The conventional two-stage lead-lag Power System Stabilizer is considered in this study. IEEE Type-ST1A Excitation system is considered. The inputs to excitation system are terminal voltage (V_T), supplementary signal (V_s) from PSS and reference voltage (V_{ref}). K_A and T_A are the gain and time constant of excitation system respectively.

The PSS takes the speed deviation signal ($\Delta\omega$) as input to produce a component of electrical torque in the direction of $\Delta\omega$ and gives a supplementary control signal (ΔV_S) to excitation system as output.

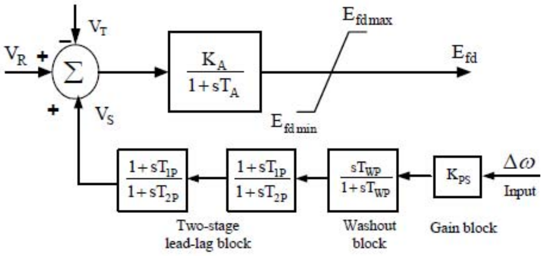

Fig 2: Structure of PSS and IEEE Type-ST1A Excitation system [11]

It consists of a wash out block to reduce over response of damping during severe events and acts as high pass filter, with time constant (T_W) high enough to allow signals associated with oscillations in input signal to pass unchanged. The lead-lag compensation blocks are responsible to produce a component of electrical torque in the direction of speed deviation ($\Delta\omega$). The gain (K_p) determines the damping level.

C. Thyristor Controlled Series Compensator (TCSC)

TCSC is one of important FACTS devices, which has been in use for many years to increase line power transfer and its performance as well as to improve system transient stability. It consists of three main components: capacitor bank C, bypass inductor L and bidirectional thyristor T_1 and T_2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, which is coded depending on system parameter variation [3, 9, 10, 11].

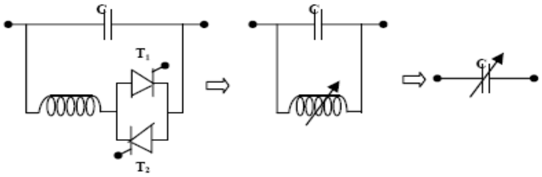

Fig 3: TCSC Configuration

The TCSC can be controlled to work either in the capacitive or the inductive zones avoiding steady state resonance. This mode is called venire control mode. The equivalent capacitive reactance provided by TCSC controller as function of firing angle is given as.

$$X_{TCSC}(\alpha) = X_C - \frac{X_C^{\,2}}{X_C - X_P}\frac{\sigma + \sin\sigma}{\pi} + \frac{4X_C^2}{(X_C - X_P)}\frac{\cos^2(\sigma/2)}{(k^2-1)}\frac{(k\tan(k\sigma/2) - \tan(\sigma/2))}{\pi} \tag{6}$$

X_C = Nominal reactance of the fixed capacitor C.
X_P = Inductive reactance of inductor L connected in parallel with C.

$\sigma = 2(\pi - \alpha)$ = Conduction angle of TCSC controller.

$k = \sqrt{\dfrac{X_C}{X_P}}$ = Compensation ratio

III. PROBLEM FORMULATION

A. TCSC Controller

The conventional lead–lag structure is chosen in this study as a TCSC controller. The structure of the TCSC controller model is shown in Fig. It consists of a gain block, signal wash out block and a two stage lead-lag phase compensation blocks. These blocks serve the same purpose as in PSS. It consists of a gain block with gain K_T, a signal washout block and two-stage phase compensation block as shown in figure. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter, with the time constant T_W (1-10sec), high enough to allow signals associated with oscillations in input signal to pass unchanged.

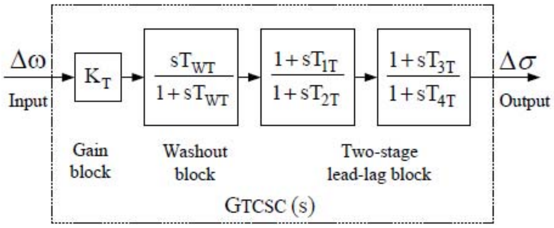

Fig 4: Structure of TCSC Controller

The damping torque contributed by TCSC can be considered to be in two parts. The first part K_P referred as direct damping torque and is directly applied to electro mechanical oscillation loop of the generator. The second part comprises of both Kq and K_V referred as indirect damping torque, applied through the field channel of generator. The damping torque contributed by TCSC controller to the electromechanical oscillation loop of the generator is:

$$\Delta T_D = T_D \omega_0 \Delta\omega \cong K_P K_T K_D \Delta\omega \qquad (7)$$

The transfer functions of the PSS and the TCSC controller are (8) and (9) respectively:

$$u_{PSS} = K_P \left(\frac{sT_{WP}}{1+sT_{WP}} \right) \left(\frac{1+sT_{1P}}{1+sT_{2P}} \right) \left(\frac{1+sT_{3P}}{1+sT_{4P}} \right) \qquad (8)$$

$$u_{TCSC} = K_T \left(\frac{sT_{WT}}{1+sT_{WT}} \right) \left(\frac{1+sT_{1T}}{1+sT_{2T}} \right) \left(\frac{1+sT_{3T}}{1+sT_{4T}} \right) \qquad (9)$$

In this structure, the washout time constants T_{WT} and T_{WP} are usually pre-specified, T_{WT}= T_{WP}=5s. The controller gains K_T & K_P and the time constants T_{1T} , T_{2T} , T_{3T} , T_{4T} , T_{1P} , T_{2P}, T_{3P}, T_{4P} are to be determined. The input signal of the proposed TCSC stabilizer is the speed deviation Δω and the output is change in conduction angle . During steady state conditions = 0 and X_{Eff} = X_T+X_L-X_{TCSC}($_0$). During dynamic conditions the series compensation is modulated for damping system oscillations. The effective reactance in dynamic conditions is: X_{Eff}= X_T+X_L-X_{TCSC}( ), where = $_0$+ and =2(-), $_0$ and $_o$ being initial value of firing & conduction angle respectively.

B. Objective Function

The design of coordinated controller is done based on minimizing the objective function considered such that power system oscillations after a disturbance or loading condition so as to improve the stability. In this approach the objective function is formulated in such way rotor speed deviation $\Delta\omega$ is minimized and mathematically formulated as follows

$$J = \sum \int_0^{t_1} t[\Delta\omega(t, X)]^2 \, dt \qquad (10)$$

In the above equations, $\Delta\omega(t, X)$ denotes the rotor speed deviation for a set of controller parameters X. Here X represents the parameters to be optimized. A total of 10 parameters (both that of TCSC and PSS controller) are been tuned to get the optimal response.

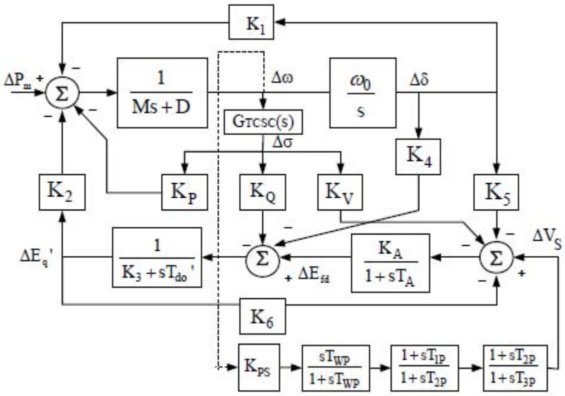

Fig 5: The Phillips-Heffron model of SMIB with TCSC and PSS [11]

IV. ARTIFICIAL BEE COLONY ALGORITHM

Artificial Bee Colony (ABC) algorithm classifies the foraging artificial bees into three groups; the *employed bees, the onlooker bees* and the *scouts.* The first half of the colony consists of the employed bees and second half consist of the onlooker bees. A bee that is currently searching for food or exploiting a food source is called an *employed bee* and a bee waiting in the hive for making decision to choose a food source is called an *onlooker bee*. For every food source, there is only one employed bee. The employed bee of abandoned food source becomes a *Scout.* In ABC algorithm each solution to the problem is considered as food source and is represented by a *D*-dimensional real-valued vector, where the fitness of the solution corresponds to the nectar amount of associated food source.

The algorithm starts by initializing all the employed bees with randomly generated food sources (solutions). In each generation/iteration every employed bee finds a food source in the neighborhood of its current food source and evaluates its *nectar* amount i.e., (*fitness*). In general the position of i_{th} food source, for a D dimensional search space, is represented as $X_i = \{x_{i1}, x_{i2}, \ldots . x_{iD}\}$ .After the information is shared by the employed bees; onlooker bees go to the region of food source at X_i based on the probability P_i defined as

$$P_i = \frac{fit_i}{\sum_{k=1}^{FS} fit_k} \tag{11}$$

FS is total number of food sources. Fitness value fit_i is calculated by using following equation.

$$fit_i = \frac{1}{1 + f(X_i)} \tag{12}$$

Here $f(X_i)$ is the objective function to be minimized. The onlooker finds its *food source* in the region X_i , by making use of following equation.

$$x_{new} = x_{ij} + r * (x_{ij} - x_{kj}) \tag{13}$$

Where $k \in (1,2,3,\ldots,FS)$ such that $k \notin i$ and $j \in (1,2,3,\ldots,D)$ are randomly chosen indexes, *r* is a uniformly distributed random number in the range [-1, 1]. If the obtained new fitness value is better than the fitness value achieved so far, than the bee moves to this new food source leaving this old one otherwise it retains the old food source. When all employed bees have completed this process, the information is shared with onlookers. Each of the onlookers selects a food source according to the probability given above. By this scheme good sources are well accommodated with onlookers. Each bee will search for a better food source for a certain number of cycles (*limit*), and if the fitness value doesn't improve then that particular bee becomes a *Scout* bee. A food source is initialized to that *scout bee* randomly and the search process continues. In this approach we used basic version which involve only one scout bee.

V. DESIGN OF COORDINATED PSS WITH TCSC CONTROLLER

A. *Parameters of power system considered*

For the small signal stability analysis of single machine infinite bus the design of the system and system data is taken from[11].

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

2. Generator: H=4.0s, D=0, X_d=1.0, X_q=0.6, X_d' =0.3, T_{d0}=5.044, f=50, R_a=0, P_e=1.0, Q_e=0.303, $\delta_0 = 60.62$

3. Exciter: (IEEE type ST1) K_A=200, T_A=0.04s.

4. Transmission line and Transformer: =0.0+j0.8 (X_L=j0.7, X_T=0.1)

5. TCSC Controller: $X_{TCSC\,0}$=0.245, $\alpha_0 = 156.04^0$, X_C=0.21, X_P=0.0525

As the optimization is to be carried out in a bounded search we had used the following ranges for different parameters in our design and they are recorded in Table I. The parameters being considered for tuning were K_T, K_P, T_{1T} , T_{2T} , T_{3T} , T_{4T} , T_{1P} , T_{2P}, T_{3P}, T_{4P} (the parameters with subscript T indicates they belong to TCSC controller and that of P indicates they belong to PSS Control. The ranges over which these parameters tuned as per standards are as given below.

Table I: Maximum and Minimum values for parameters considered [12]

TCSC Controller		PSS	
Parameter	Range	Parameter	Range
K_T	30-80	K_P	30-80
T_{1T}	0.1-0.6	T_{1P}	0.1-0.6
T_{2T}	0.02-0.4	T_{2P}	0.02-0.4
T_{3T}	0.1-0.6	T_{3P}	0.1-0.6
T_{4T}	0.02-0.4	T_{4P}	0.02-0.4

B. *Parameters of Artificial Bee Colony Algorithm*

The objective function considered is a 10-Dimensional optimization function hence we considered a maximum of 4000 Functional Evaluations as a termination criteria for designing the coordinated PSS-TCSC controller and rest of parameters are recorded in Table II.

Table II Algorithmic Parameters (ABC and L-ABC)

Parameter	**Value**
No of Bees (NB)	20
Food Sources (FS)	NB/2
Employed Bees	*50% of bees*
Onlooker Bees	*50% of bees*
Scout Bees	1
Limit	n_e*D

VI. SIMULATIONS AND RESULTS

In this context we considered three different loading conditions and they are as follows

1. Nominal Loading: P_e=1.0, Q_e=0.303
2. Light Loading: P_e=0.3, Q_e=0.015 and system inertia reduces by 25%
3. Heavy Loading: P_e=1.01, Q_e=0.1 and total line reactance increases by 30%.

For a step change of 5% in load the above loading conditions are considered and been designed using ABC.

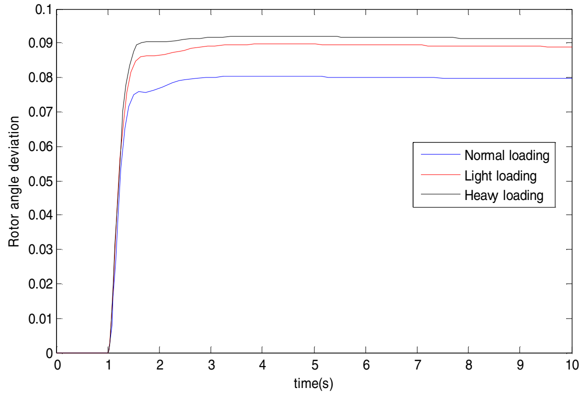

Fig 6: For a Step Change of 5% load Rotor angle deviation for different loading conditions

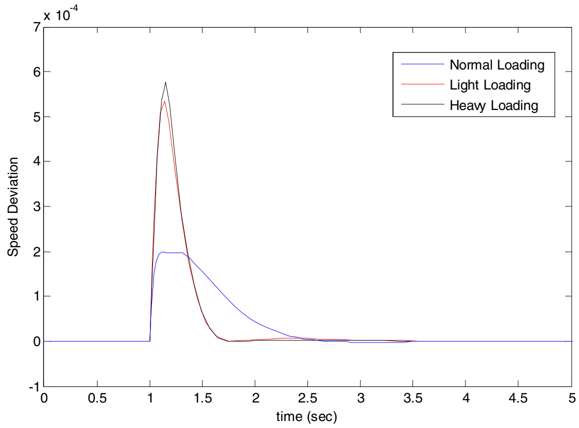

Fig 7: For a Step Change of 5% load Speed deviation for different loading conditions

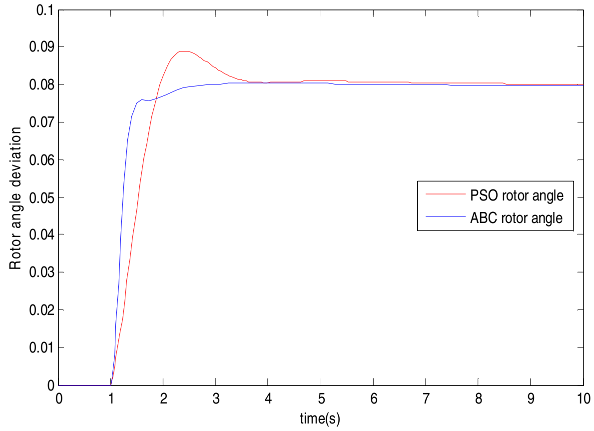

Fig 8: For a Step Change of 5% load comparison of Rotor angle deviation for ABC tuned TCSC to that of PSO [10] tuned TCSC

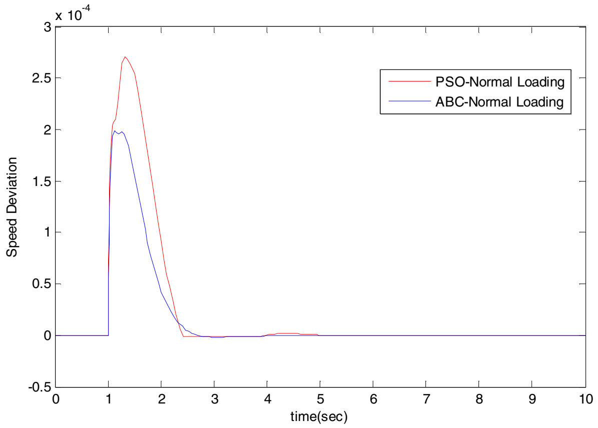

Fig 9: For a Step Change of 5% load comparison of Speed deviation for ABC tuned TCSC to that of PSO [10] tuned TCSC

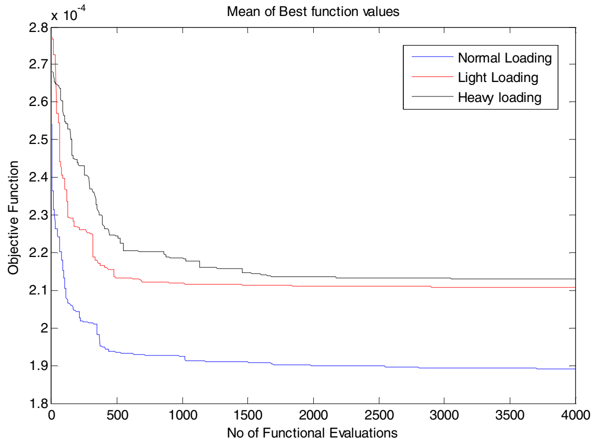

Fig 10: Convergence Characteristics of ABC towards optimum for different loading conditions

From the above simulations (Fig 6, Fig 7) it is very clear that ABC designed PSS-TCSC controller had shown good performance and also the algorithm convergence are also found to be very promising from above Fig 10. To further demonstrate the performance of our proposed approach we had compared our results to that of PSO designed PSS-TCSC controller and from the Fig 8, Fig 9 it is very clear that ABC had outperformed PSO in designing the PSS-TCSC Controller. In Table III we recorded different parametric values obtained when designing coordinated PSS-TCSC controller using ABC. In Table IV we provided the obtained fitness along with standard deviation (for 25 runs considered).

Table III: Parametric Values Obtained Using ABC

	Nominal Loading	Heavy Loading	Light Loading
K_{TCSC}	30.0000	30.0000	30.3380
T_{1T}	0.1839	0.1432	0.2855
T_{2T}	0.1672	0.3699	0.2821
T_{3T}	0.3029	0.1174	0.5080
T_{4T}	0.3084	0.4000	0.3216
K_{PSS}	30.0000	30.0000	30.0370
T_{1P}	0.2719	0.1388	0.1000
T_{2P}	0.1864	0.3861	0.4000
T_{3P}	0.1256	0.6000	0.3197
T_{4P}	0.4000	0.1667	0.4000

Table IV: Mean and Standard Deviation for Different Loading Conditions

Loading Condition	Mean	Std
Normal Loading	1.8919e-004	9.4445e-007
Light loading	2.1072e-004	1.5978e-007
Heavy Loading	2.1296e-004	1.1129e-006

VII. CONCLUSIONS

In this paper we proposed a new intelligent method of designing a coordinated PSS-TCSC controller using a new swarm intelligent Artificial Bee Colony algorithm. We also considered three loading conditions to validate the superiority of our approach in coordinated design. From the simulations and results section it is very clear that ABC had outperformed PSO based method. Our future research would be developing Thyristor controlled phase shifter (TCPS) installed single machine infinite bus (SMIB) using evolutionary methods.

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