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Power System Stability Improvement via TCSC Controller Employing a Multi-objective Strength Pareto Evolutionary Algorithm Approach

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ABSTRACT
This paper focuses on multi-objective designing of multi-machine Thyristor Controlled Series Compensator (TCSC) using Strength Pareto Evolutionary Algorithm (SPEA). The TCSC parameters designing problem is converted to an optimization problem with the multi-objective function including the desired damping factor and the desired damping ratio of the power system modes, which is solved by a SPEA algorithm. The effectiveness of the proposed controller validates on a multi-machine power system over a wide range of loading conditions. The results of the proposed controller (SPEATCSC) are compared with the Genetic Algorithm (GA) based tuned TCSC through some operating conditions to demonstrate its superior efficiency.

KEYWORDS: TCSC Design, Strength Pareto Evolutionary Algorithm, Multi-machine Power System, Genetic Algorithm, Power Oscillation Damping.

1. INTRODUCTION

Recent development of power electronics introduces the use of flexible AC transmission system (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the stability of a power system [1]. thyristor controlled series compensator (TCSC) is one of the important members of FACTS family that is increasingly applied with long transmission lines by the utilities in modern power systems. TCSC is a series FACTS device, which allows rapid and continuous changes of the transmission line impedance [2]. TCSC is also a type of series compensator, can provide many benefits for a power system including controlling power flow in the line, damping power oscillations, and mitigating sub-synchronous resonance [3].

In recent years, numerous schemes have been posed for designing TCSC to enhance the damping of electromechanical oscillations of power systems and application of different optimization techniques in improving power system stability. A pole placement technique for PSS and TCSC based stabilizer using simulated annealing (SA) algorithm was presented in [4]. A procedure for modeling and tuning the parameters of TCSC compensation controller in a multi-machine power system to improve system stability using genetic algorithm (GA) was introduced in [5]. The application and performance comparison of particle swarm optimization (PSO) and GA optimization techniques for FACTS based controller design was discussed in [6]. A new design procedure for simultaneous coordination designing of the TCSC damping controller and PSS in multi-machine power system was developed in [7] using PSO. The influence of TCSC on the

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steady state voltage stability was investigated in [8]. The line stability index (LSI) under excepted lines outage contingencies was used to identify the critical line which is considered as the best location for TCSC. A modal analysis was used to define the weakest bus of the studied system. The TCSC device was implemented and included into the Newton-Raphson power flow algorithm, and the control function was formulated to achieve the voltage stability enhancement goal. In Ref. [9] a genetic algorithm for designing PSS with TCSC as a member of FACTS family was presented in order to enhance small disturbance stability. To increment damping of electromechanical mode and improve small disturbance stability, a lead-lag controller was also used and the effective-eness of the proposed controllers was verified on a single machine infinite bus (SMIB) power system. The loadability enhancement using optimal number and location of FACTS devices for combined pool and bilateral transactions using mixed integer nonlinear programming (MINLP) was determ-ined utilizing secured bilateral transaction matrix using DC distribution factor [10]. In Ref. [11] an algorithm was proposed for the optimal location and control of TCSC for enhancing the loadability in transmission system using particle swarm optimization and differential evolution (DE) for pool and hybrid model deregulated electricity market. The proposed approach uses AC load flow equations with the constraints on power generation, transmission line flow, magnitude of bus voltages and FACTS device settings. The bilateral transactions are modeled using secured bilateral transaction matrix utilizing AC distribution factor with the slack bus contribution and simulated on 39 bus New England test system and IEEE 118 bus system to indicate its robust performance. In Ref. [12] TCSC-FACTS general type controller was used to enhance power system performance, improve quality of supply and also provide an optimal utilization of the existing resources. The proposed TCSC based controller performance analysis was carried out for different cases such as short circuit fault, open circuit fault to illustrate validity. A supplementary damping control system design for TCSC based on natural inspired virtual bees algorithm (VBA) was presented in [13]. A method to simulate the nonlinear performance of TCSC and evaluation of impact of TCSC on power system stability was proposed in [14]. Coordination of TCSC controllers conducted by applying a linear matrix inequality was discussed in [15]. A probabilistic evaluation of total transfer capability and its improvement using probabilistic model of FACTS devices were presented in [16]. A coordinated control scheme for excitation systems and TCSC control for improving the stability of a power system were addressed in [17]. The control scheme was developed with nonlinear optimal variable aim strategies. A novel scheme of damping power system multimode oscillations by using a single FACTS device was illustrated in [18]. A reduced rule base self-tuning fuzzy PI controller (STFPIC) for TCSC was proposed in [19]. The application of the decentralized modal control method for pole placement in multi-machine power system utilizing FACTS devices was developed in [20]. A small signal model of single-machine infinite bus power system installed with a TCSC where the parameters of the TCSC damping controller optimized by a multi-objective genetic algorithms was repre-sented in [21].

In this paper, a new optimization scheme known as strength Pareto evolutionary algorithm (SPEA) is presented for optimal design of damping controller for TCSC in a multi-machine power system to reduce power system oscillations. The TCSC parameters designing problem is converted to an optimization problem including damping factor and damping ratio for different operating conditions. The effectiveness of the proposed approach is confirmed on multi-machine power systems under different operating conditions and disturbances. The results of tuned TCSC controller based on SPEA is compared with genetic algorithm based TCSC to validate the superiority of the proposed technique.

2. PROBLEM FORMULATION

2.1. Power system model

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

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

The linearized incremental models around an equilibrium point are usually employed in the design of TCSC. Hence, the state equation of a power system with *n* machines and *m* TCSC can be formulated as follows:

$$\dot{X} = AX + BU \quad (2)$$

Definitions of symbols are as follows: X is the vector of the state variables; U is the vector of input variables; in this paper $X = [\delta, \omega, E_q', E_{fd}, V_f]^T$ and U includes TCSC output signals; δ and ω are the rotor angle and speed, respectively. E_q', E_{fd} and V_f are the internal, the field, and excitation voltages, respectively; A is a $5n \times 5n$ matrix and equals $\partial f/\partial X$; B is a $5n \times m$ matrix and equals $\partial f/\partial U$; X is a $5n \times 1$ state vector; U is an $m \times 1$ input vector.

2.2. System under study

The single line diagram of the test system used in this study is depicted in Fig. 1. The system data are represented in [22]. The eigenvalues and frequencies connected to the rotor oscillation modes of the system are tabulated in Table 1. As it can be seen from the Table, the 0.2371 Hz mode is the inter-area mode with G1 oscillating against G2 and G3. 1.2955 and 1.8493 Hz modes are the inter-machine oscillation local to G2 and G3, respectively. Furthermore, instability of the system is revealed by the positive real part of proper value of G1. Table 2 shows the system and generator loading levels.

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

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

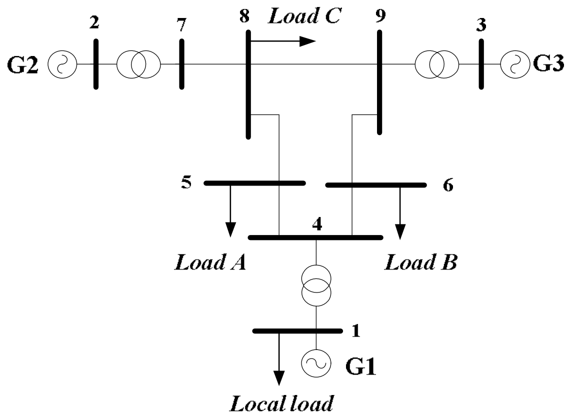

Fig. 1. System under study

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

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

Table 2. Loading condition for the system

Gen	Light		Normal		Heavy	
	P	Q	P	Q	P	Q
G1	0.9649	0.223	1.7164	0.6205	3.5730	1.8143
G2	1.0000	-0.1933	1.630	0.0665	2.20	0.7127
G3	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

2.3. TCSC model

A typical TCSC module consists of a fixed series capacitor in parallel with a thyristor controlled reactor (TCR). The TCR is formed by a reactor in series with a bi-directional thyristor valve which is fired by a phase angle α, ranging between 90 and 180° with respect to the capacitor voltage. For the load flow and dynamic stability analysis studies, a TCSC can be modeled as a variable reactance.

The dynamic equation of TCSC reactance can be expressed as follow:

$$\Delta \dot{X}_{TCSC} = \frac{1}{T_S}(K_S(\Delta X_{TCSC}^{ref} + \Delta U_{TCSC}) - \Delta X_{TCSC}) \quad (3)$$

where, X_{TCSC}^{ref} is the reference reactance of the TCSC; K_S and T_S are the gain and time constants of TCSC**.**

Figure 2 illustrates the block diagram of the TCSC based damping controller.

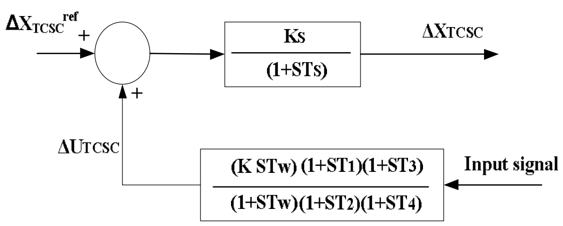

Fig. 2. Block diagram of TCSC

Many input signals have been proposed for the FACTS to damp the system oscillations. Signals, which carry invaluable information about the inter-area mode, can be considered as the input signals. Since FACTS controllers are located in the transmission systems, local input signals are always preferred. For example, line active power and current carry such valuable information. Transmission line active power has been proposed as an effective input signal in [15] for series FACTS devices damping controller design. For this reason, here, the active power of the transmission line is selected as the input signal. The line flow data are tabulated in Table 3. The line 5-7 has the largest power flow as well as being the longest line in the system and it will be assumed as the best candidate to install the TCSC.

2.4. Objective function

In order to provide greater damping, a multi-objective function comprising the damping factor and the damping ratio is considered as follows [23]:

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

where, n_p is the number of operating points considered in the design process; *r* and *n* are the real part and the damping ratio of the eigenvalue of the operating point.

The major goal is to minimize *J*, as the sequel:

$$OF : Minimize(J) \quad (5)$$

This will place the closed loop eigenvalues of the system in the D-shape sector characterized as depicted in Fig. 3.

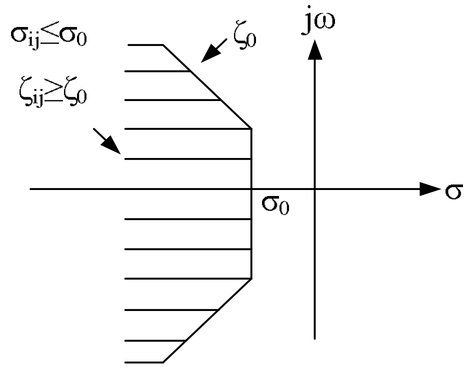

Fig. 3. D-shape sector in the s-plane

In this paper, σ_0 and ζ_0 are selected to be -0.5 and 0.1, respectively.

Table 4. TCSC boundaries

Parameters	T_1	T_2	T_3	T_4	K
Minimum	0.01	0.01	0.01	0.01	0.01
Maximum	1.0	1.0	1.0	1.0	50

In order to reduce the computational burden, the limitation of the parameters is tabulated in Table 4. Enhancing the damping properties as well as acquiring a good performance through different operating conditions are the main contribution of optimization process.

3. STRENGTH PARETO EVOLUTIONARY ALGORITHM

One of the most successful multi-objective optimization approaches is the SPEA [24] which is based on Pareto optimality concept.

Definition: Concept of Pareto optimality can be described mathematically as below:

The vector a in the search space dominates vector b if

$$\forall_i \in \{1,2,...,k\}: f_i(a) \geq f_i(b)$$
$$\exists_j \in \{1,2,...,k\}: f_j(a) > f_j(b) \quad (6)$$

If at least one vector dominates b, then b is considered dominated vector, otherwise it is called non-dominated. Each non-dominated solution is regarded optimal in the sense of Pareto or called Pareto optimal. Obviously, any Pareto optimal solution is comparatively the most optimal one in terms of at least one of the objective functions. The set of all non-dominated solutions is called Pareto optimal set (POS) and the set of the corresponding values of the objective functions is called Pareto optimal front (POF) or simply Pareto front.

The SPEA, which takes benefits from many features of some other approaches, is used in this paper. Fig. 4 shows a flowchart of the approach, which includes the following major steps [17]:

Step 1. Generate an initial population *P* and create the empty external non-dominated set *P*.

Step 2. Paste non-dominated members of *P* into *P'*.

Step 3. Remove all solutions within *P'* covered by any other members of *P'*.

Step 4. If the number of externally stored non-dominated solutions exceeds a given maximum *N'*, prune *P'* by means of clustering.

Step 5. Calculate the fitness of all individuals in *P* and *P'*.

Step 6. Use binary tournament selection with replacement and select individuals from *P* and P' until the mating pool is filled.

Step 7. Apply crossover and mutation operators as usual.

Step 8. If the maximum number of generations is reached, then stop, else go to step 2.

Fitness evaluation is also performed in two steps. First, the individuals in the external non-dominated set *P'* are ranked. Then, the individuals in the population *P* are evaluated. For more details, refer to [17].

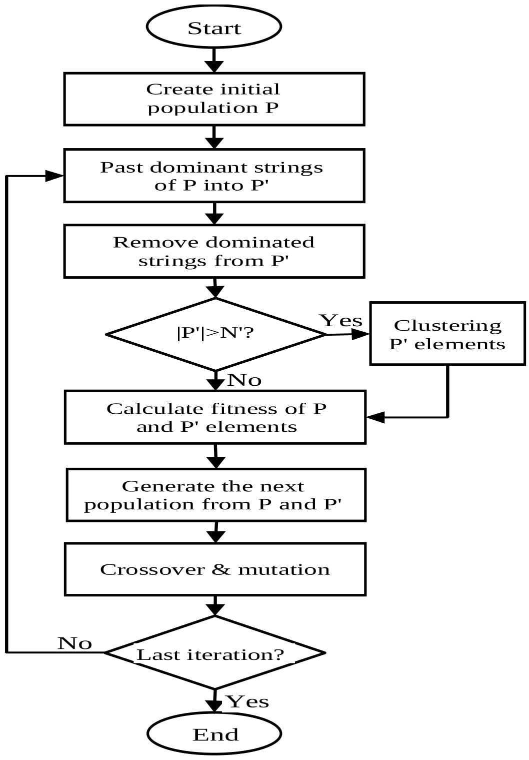

Fig. 4. SPEA flowchart

4. SIMULATION RESULT

4.1. Determination of parameters for SPEA

The proposed SPEA methodology is programmed in MATLAB running on an Intel w Core TM2 Duo Processor T5300 (1.73 GHz) PC with 1 GB RAM. It is applied on a multi-machine power system to demonstrate its abilities. The effect of SPEA parameters on average fitness function (among 200 trials) is investigated. The colony size (N_C) tried was 200. One hundred independent trials have been made with 200 iterations per trial. The performance of the SPEA also depends on the number of colonies. The parameters of SPEA are selected based on the average fitness function. After a number of careful experimentation, following optimum values of SPEA parameters have finally been settled as shown in Table 5. In addition, Table 5 shows the optimum values obtained for GA parameters.

Table 5. SPEA and GA Simulation parameters

Method	Parameters
SPEA	*Nc* = 200; Mutation = 0.036; Length of the chromosome: 5 for each variable; Recombination: single-point crossover
GA	*Nc*=200; Normalized geometric selection; Simple Xover; Binary mutation

4.2. Comparing result

The minimum fitness value evaluating process is depicted in Fig. 5. As it can be seen from the figure, the convergence of SPEA is faster than GA. This is because SPEA algorithm provides the correct answers with high accuracy in the initial iterations, which makes the responding time of this algorithm extremely fast. The system eigenvalues and damping ratio of mechanical mode with three different loading conditions is tabulated in Table 6. The instability of open loop system for light, normal, and heavy loading conditions can be easily observed from the Table. The SPEATCSC shifts significantly the electromechanical mode eigenvalues to the left of the S-plane. Consequently, the values of the damping factors are considerably improved to (ζ = -0.65, -0.62, -0.85) for light, normal, and heavy loading respectively. Table 7 shows optimized parameters values of different controllers based on the time domain objective function through the proposed SPEA technique

4.3. Light load condition

The robust efficiency of the proposed SPEATCSC is confirmed by implementing a three-phase fault of 6-cycle duration at 1 *s* near bus 7. The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$ and $\Delta\omega_{13}$ owing to severe disturbance for light loading condition are shown in Figs. 6-8. It is clear from the figures that the proposed controller attains better performance and supplies superior damping compared with the other technique. The required mean times to diminish these oscillations (settling time) are nearly 2.46 *s* and 2.86 *s* for SPEATCSC and GATCSC, respect-ively. Therefore, the designed controller is able to achieve adequate damping to the system oscillatory modes. Additionally, the oscillations are grown quickly in the case of open loop system.

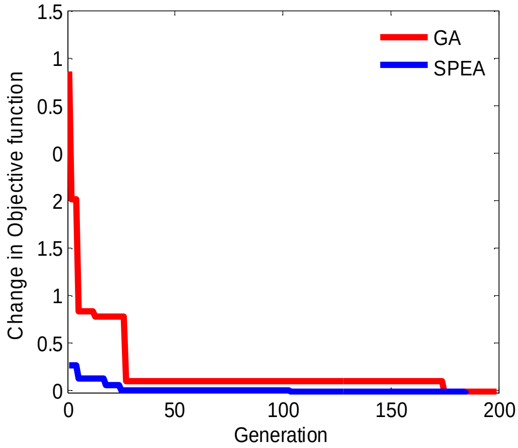

Fig. 5. Convergence profile for SPEA and GA

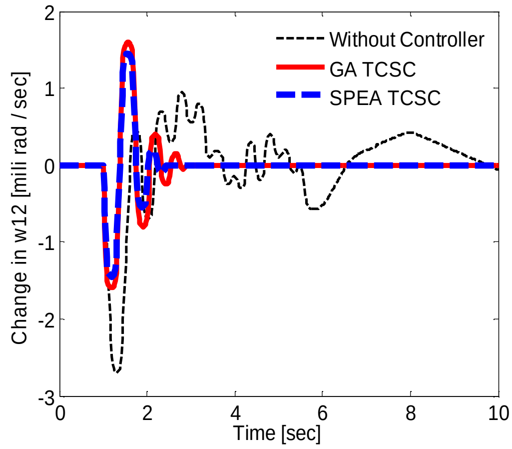

Fig. 6. Response of $\Delta\omega_{12}$ for light load condition

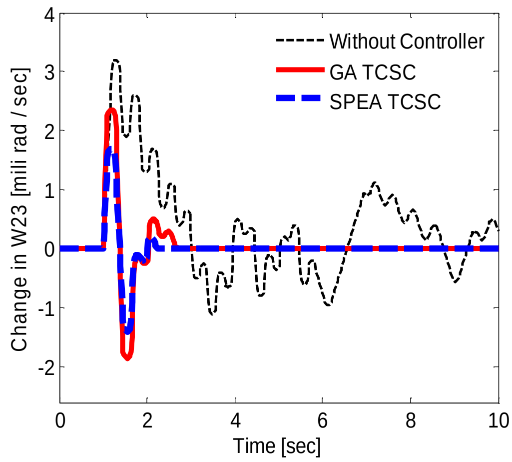

Fig. 7. Response of $\Delta\omega_{23}$ for light load condition

Table 6. Mechanical modes and ζ under different loading conditions and controllers

Load	Without TCSC	SPEATCSC	GATCSC
Light	-0.79±9.83j, 0.0801	-3.94±9.02j, 0.4116	-3.24±8.91j, 0.3485
	-0.58±7.85j, 0.0737	-2.06±6.11j, 0.3250	-1.91±6.39j, 0.2903
	+0.05±0.92j, -0.054	-0.65±0.658j, 0.7788	-0.51±0.697j, 0.6313
Normal	-0.58±11.83, 0.04896	-3.21±11.48j, 0.2725	-2.96±11.51j, 0.2515
	-0.29±8.47j, 0.0342	-1.36±6.19j, 0.2116	-0.97±6.13j, 0.1568
	+0.14±1.79j, -0.78	-0.62±0.71j, 0.7174	-0.58±0.725j, 0.6743
Heavy	-0.48±12.15, 0.039	-3.66±11.12j, 0.3181	-2.91±11.31j, 0.2517
	-0.16±8.73j, 0.0183	-0.86±5.43j, 0.1569	-0.712±5.86j, 0.1208
	+0.052±2.04j, -0.025	-0.85±0.738j, 0.8553	-0.79±0.831j, 0.7597

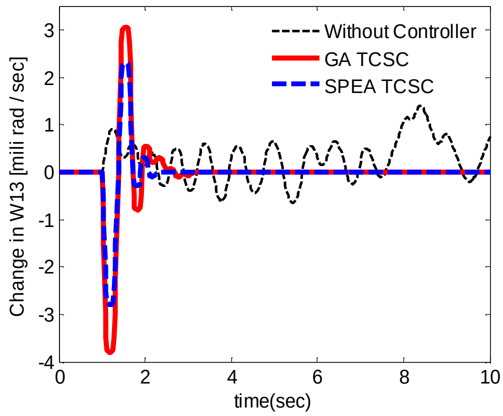

Fig. 8. Response of $\Delta\omega_{13}$ for light load condition

Table 7. Optimal TCSC parameters based on SPEA and GA techniques

Parameters	GATCSC	SPEATCSC
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

4.4. Normal load condition

The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$ and $\Delta\omega_{13}$ owing to same disturbance for normal loading condition are depicted in Figs. 9-11. 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 mean settling times are Ts = 2.48 s and 3.24 s for SPEATCSC and GATCSC respectively. The instability of open loop system is clear from the figures. Consequently, the ability of attaining better system oscillation damping by SPEATCSC is verified by comparing with GATCSC as well as open loop case.

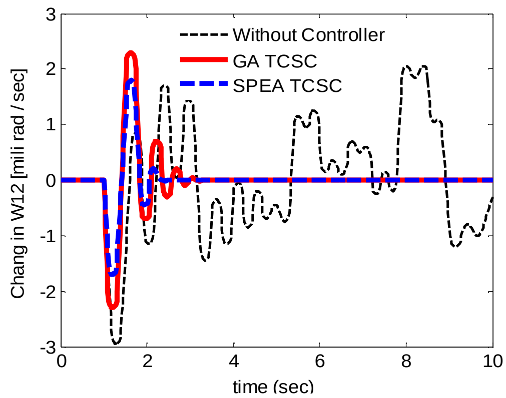

Fig. 9. Response of $\Delta\omega_{12}$ for normal load condition

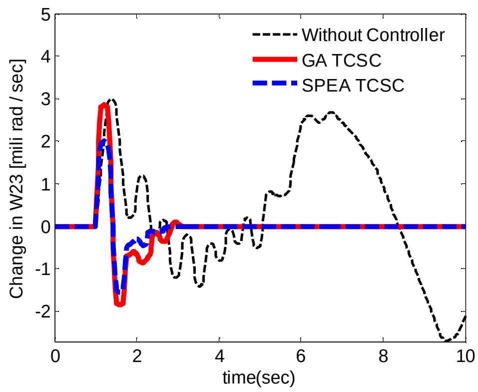

Fig. 10. Response of $\Delta\omega_{23}$ for normal load condition

4.5. Heavy load condition

The response of $\Delta\omega_{12}$, $\Delta\omega_{23}$ and $\Delta\omega_{13}$ for heavy loading condition are illustrated in Figs. 12-14. It is obvious from the figures that the proposed SPEATCSC controller demonstrates better damping properties to low frequency oscillations and faster stability in comparison with GATCSC. The mean settling time are Ts = 2.76 s and 3.22 s for SPEATCSC and GATCSC, respectively. Consequently, the power transfer ability as well as the power system stability are increased using the proposed SPEATCSC controller.

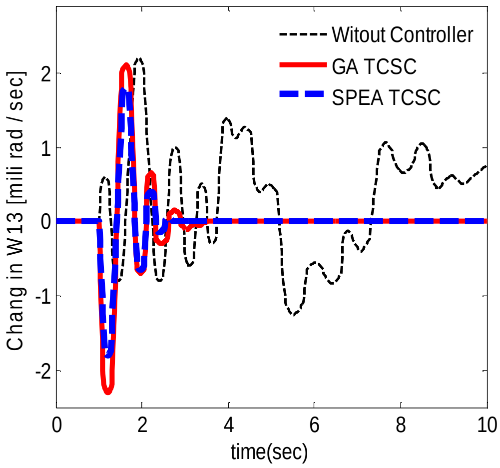

Fig. 11. Response of $\Delta\omega_{13}$ for normal load condition

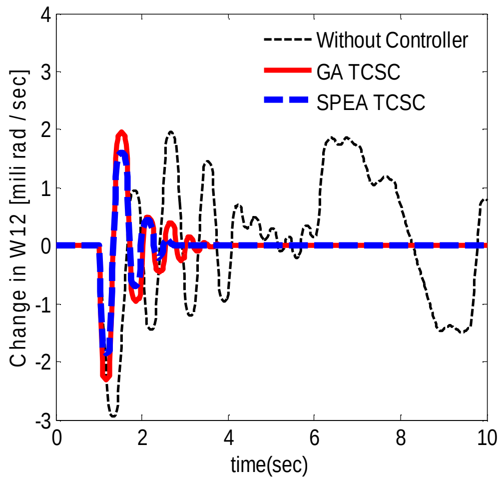

Fig. 12. Response of $\Delta\omega_{12}$ for heavy load condition

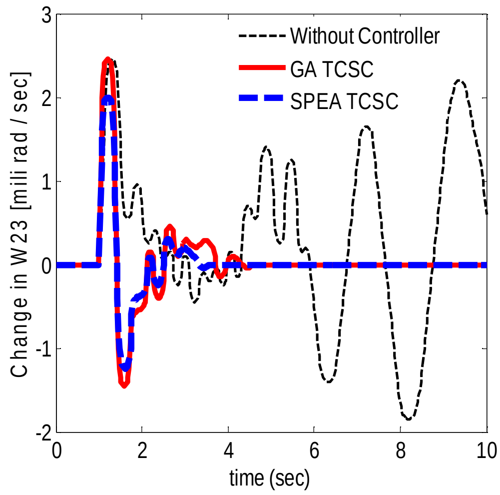

Fig. 13. Response of $\Delta\omega_{23}$ for heavy load condition

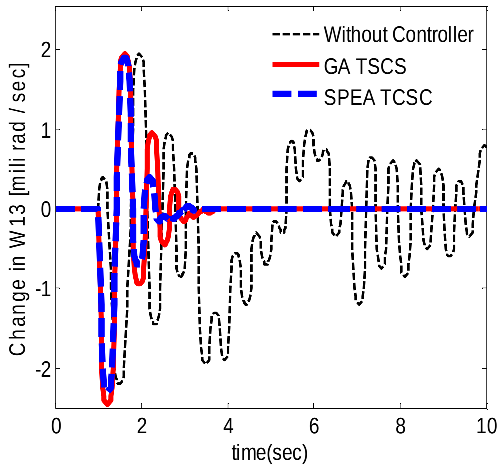

Fig. 14. Response of $\Delta\omega_{13}$ for heavy load condition

5. CONCLUSIONS

This paper proposes a novel strength Pareto evolutionary algorithm based TCSC (SPEATCSC) to mitigate power system oscillations in a multi-machine area. The proposed design problem of TCSC over a wide range of loading conditions is formulated as an optimization problem with the multi-objective function reflecting the combination of damping factor and damping ratio. 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 GA 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 optima
- Providing the correct answers with high accuracy in the initial iterations
- Superiority in computational simplicity, success rate and solution quality.

APPENDIX

Genetic algorithm

It is well known that GAs work according to the mechanism of natural selection – stronger individuals are likely to be the winners in a competitive environment. In practical applications, each individual is codified into a chromosome consisting of genes, each representing a characteristic of one individual. For identification of the unknown parameters of a model, parameters are regarded as the genes of a chromosome, and a positive value, generally known as the fitness value, is used to reflect the degree of goodness of the chromosome [25, 26]. Typically, a chromosome is structured by a string of values in binary form, which the mutation operator can operate on any one of the bits, and the crossover operator can operate on any boundary of each two bits in the string. Since in our problem the parameters are real numbers, a real coded GA is used, in which the chromosome is defined as an array of real numbers with the mutation and crossover operators. Here, the mutation can change the value of a real number randomly, and the crossover can take place only at the boundary of two real numbers. More details of the proposed GA is shown in Fig. 15.

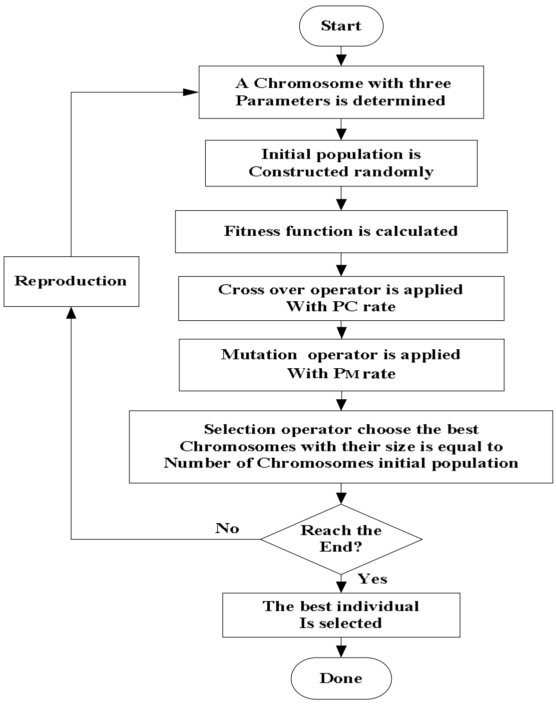

Fig. 15. GA flowchart

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