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Coordinated Design of Power System Stabilizers and TCSC using Cat Swarm Optimization Algorithm

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ABSTRACT

Power System Stabilizers (PSS) are used to damp electromechanical oscillations by providing auxiliary stabilizing signals to the excitation system of the generators. The Conventional PSS (CPSS) do not provide sufficient damping for inter-area oscillations in multi-machine power systems. Thyristor Controlled Series Capacitor (TCSC) has immense potential in damping of inter-area power swings and in mitigating the sub-synchronous resonance. In this paper Cat Swarm Optimization (CSO) algorithm is used for coordinated design of multiple PSS and TCSC for effective damping of the oscillations. The results obtained by using CSO algorithm on WSCC 3-machine, 9-bus system are found superior compared to the results obtained using Bacterial Swarm Optimization (BSO) algorithm. The damping performance of PSS and TCSC controllers when they are designed independently using CSO is compared with coordinated design of PSS and TCSC with CSO algorithm on New England 10-machine, 39-bus system over wide range of operating conditions and disturbances. To demonstrate the effectiveness of the proposed technique the results obtained using CSO on this test system are also compared with the results obtained with Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Bacterial Swarm Optimization (BSO).

Keywords: Cat Swarm Optimization, Damping, Power System Stabilizers, TCSC, Multi-machine Power System

1. INTRODUCTION

Low frequency oscillations are observed when large power systems are interconnected by relatively weak tie-lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1]. Conventional Power System Stabilizers (CPSS) are widely used by utilities to damp these oscillations and improve system dynamic stability. CPSS based on linear control theory can be very well tuned to an operating condition and will provide excellent damping over a certain range around the design point. However, CPSS parameters may not be optimal for the whole set of possible operating conditions and configurations and therefore other effective alternatives are needed in addition to PSS. With the advent of Flexible AC Transmission Systems (FACTS) devices, one of the recent plans to alleviate such conditions is by controlling the power flow along the transmission lines which improves power oscillations damping [2]. Among these FACTS devices, the Thyristor Controlled Series Capacitor (TCSC) is a multi-functional FACTS controller, which allows quick and continuous changes of the transmission line impedance. TCSC has immense potential and application in precisely regulating the power flow on a transmission line, mitigating the sub-synchronous resonance, improving the transient stability and damping inter-area power swings [3]. However, uncoordinated local control of TCSC controller and PSS may cause unwanted interactions that may further result in system destabilization. To improve overall system performance, many studies were made on the coordination among PSS and FACTS controllers [4-6]. Unfortunately, the problem of coordinated design of conventional power oscillation damping controllers is a multimodal

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optimization problem and conventional tuning methods may not provide sufficient damping for stabilizing inter-area oscillations. Hence the meta-heuristic methods, which are widely used for global optimization problems, have been used to solve this coordinated design problem.

In recent years, little work has been reported in the literature on the coordination problem investigation of PSS and TCSC controller for multi-machine power systems. Global optimization techniques like Genetic Algorithm (GA) [7], Particle Swarm Optimization (PSO) [8] and Bacterial Swarm Optimization (BSO) [9] are attracting the attention for coordinated design of robust excitation and FACTS-based controllers in the recent times. GA exhibits degraded efficiency when the system has a highly *epistatic* objective function (i.e., where the parameters being optimized are highly correlated) and number of parameters to be optimized are large [10]. PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. Further, PSO algorithm cannot solve the problems of scattering and non-coordinate system optimization [11]. Cat swarm optimization (CSO) algorithm is a recently developed swarm intelligence algorithm, based on the alertness of cats. In CSO, resting of cats with slow movement is represented by seeking mode and chasing with high speed represented by tracing mode, respectively. Compared with other heuristic algorithms, CSO algorithm is simple and performs better than PSO with respect to convergence speed [12]. The important property of CSO is that in each iteration it performs both local search as well as global search independently.

In this paper, CSO is introduced for coordinated tuning of the parameters of PSS and TCSC controllers simultaneously. By minimizing the objective function in which the influences of both PSS and TCSC controllers are considered simultaneously, interactions among these controllers are improved. These controllers have been applied and tested on New England 10-machine, 39-bus system under wide range of loading conditions and severe disturbances. The eigenvalue analysis and non-linear simulation results are presented to demonstrate the effectiveness and robustness of the proposed controllers in damping low frequency inter-area oscillations.

2. STATEMENT OF THE PROBLEM

2.1. Modeling of Power System

A power system can be modelled by a set of nonlinear differential equations as

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

where X is the vector of the state variables, and U is the vector of input variables. In this study, all the generators in the power system are represented by their fifth order models and equipped with single time constant fast exciters.

For a given operating condition, the multi-machine power system is linearized around the operating point. The closed loop eigenvalues of the system are computed and the desired objective function is formulated using only the unstable or lightly damped electromechanical eigenvalues, keeping the constraints of all the system modes stable under any condition.

2.2. PSS Structure

The speed based conventional PSS considered in the study is shown in Figure 1.

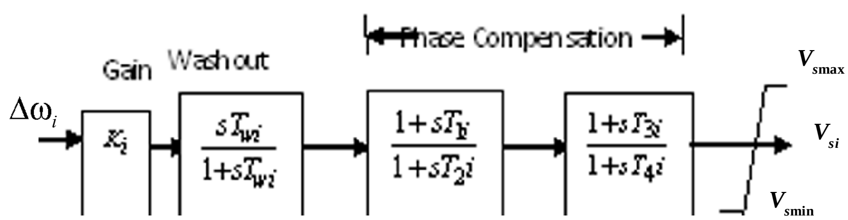

Figure 1: Structure of PSS

Here $\Delta\omega_i$ is the deviation of the speed of the rotor from synchronous speed. The $\frac{sT_{wi}}{1+sT_{wi}}$ term in the above diagram is the washout term with a time constant T_{wi}, which is generally 10 to 20 sec. The washout block serves as a high-pass filter to allow signals in the range of 0.2–2.0 Hz associated with rotor oscillations. T_w is chosen such that undesirable generator voltage excursions during system-islanding are eliminated. The phase compensation block provides compensation for the phase lag/lead that is introduced in the circuit between the exciter input (i.e. PSS output) and the electrical torque. In this study T_{wi}=10 sec and the parameters to be optimized are{K_i, T_{1i}, T_{2i}; i = 1, 2, 3, ... m where m is the number of generators}, assuming $T_{1i} = T_{3i}$, and $T_{2i} = T_{4i}$

2.3. TCSC Structure

The structure of the TCSC is shown in Figure 2.

Here K_{TCSC} is TCSC gain and T_w is washout time constant. In this study, T_w = 10 sec and $T_1 = T_3$ and $T_2 = T_4$ are used. For TCSC damping controller design, transmission line active power has been proposed as an effective input signal [13].

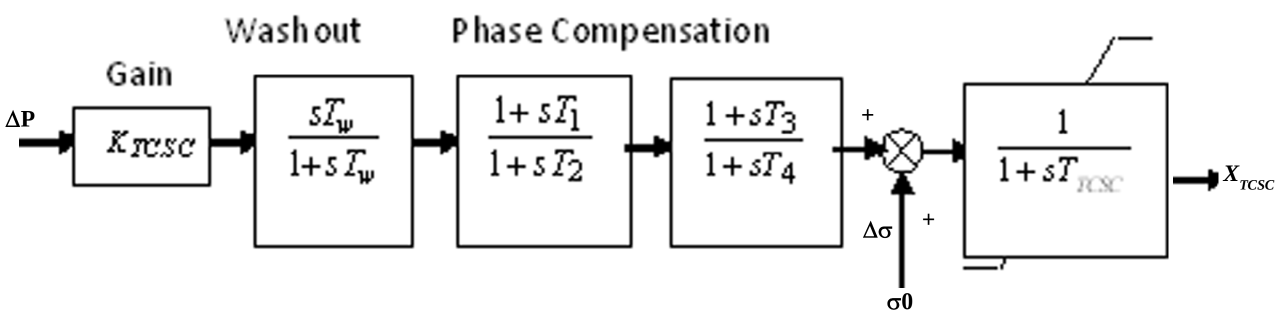

Figure 2: Structure of TCSC Controller

2.4. Objective Function

In this paper, a comprehensive assessment of the effects of coordinated application of PSS and TCSC damping controllers has been carried out. A multi-objective problem is formulated to optimize a composite set of two eigenvalue-based objective functions comprising the desired damping factor and damping ratio of the lightly damped and undamped electromechanical modes. The use of the first objective function will result in PSS that shift the lightly damped and undamped electromechanical modes to the left-hand side of a vertical line in the complex s-plane, resulting in improved damping factor. The use of the second objective function will yield PSS and TCSC settings that place these modes in a wedge-shape sector in the complex s-plane, thus improving the damping ratio of these modes. Consequently, the use of the multi-objective function guarantees the improvement of relative stability and minimization of peak overshoot.

The parameters of PSS and TCSC are tuned simultaneously so as to minimize the following objective function

$$J = J1 + \alpha .J2 \tag{2}$$

where,

$$J1 = \sum_{j=1}^{Np} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 \tag{3}$$

and

$$J2 = \sum_{j=1}^{Np} \sum_{\zeta_{i,j} \leq \zeta_0} [\zeta_0 - \zeta_{i,j}]^2 \tag{4}$$

α is a positive constant.

Here $\sigma_{i,j}$ is the real part and $\zeta_{i,j}$ is the damping ratio of i^{th} eigenvalue of j^{th} operating point, subject to the constraints that finite bounds are placed on the power system stabilizer parameters.

It is necessary to mention here that only the unstable or lightly damped electromechanical modes of oscillations are relocated. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PSS parameter bounds:

Minimize J subject to

$$\begin{aligned}
K_{i\min} &\leq K_i \leq K_{i\max} \\
T_{1i\min} &\leq \mathrm{T}_{1i} \leq \mathrm{T}_{1i\max} \\
T_{2i\min} &\leq \mathrm{T}_{2i} \leq \mathrm{T}_{2i\max} \\
K_{TCSC\min} &\leq K_{TCSC} \leq K_{TCSC\max} \\
T_{1\min} &\leq T_1 \leq T_{1\max} \\
T_{2\min} &\leq T_2 \leq T_{2\max}
\end{aligned} \tag{5}$$

In this study, σ_0 and ζ_0 are chosen to be -2.0 and 20% respectively. Several values for weight α are tested and it is observed that effect of α on final goal is minimal. Here α is taken as 10 [14]. Typical ranges of the optimized parameters for PSS are [0.01, 50] for K_i and [0.01, 1.0] for T_{1i} and T_{2i}. TCSC bounds are [0.01, 100] for K_{TCSC} and [0.01, 1.0] for T_1 and T_2.

3. CAT SWARM OPTIMIZATION

3.1. Overview

Chu and Tsai (2007) proposed cat swarm optimization algorithm which imitates the natural behavior of cats [15]. Cats have a strong curiosity towards moving objects and possess good hunting skill. Even though cats spend most of their time in resting, they always remain alert and move very slowly. When the presence of a prey is sensed, they chase it very quickly spending large amount of energy. These two characteristics of resting with slow movement and chasing with high speed are represented by seeking and tracing, respectively. In CSO these two modes of operations are mathematically modeled for solving complex optimization problems. The flow chart of Cat Swarm Optimization is given in Figure 3.

3.1.1. Seeking mode

The seeking mode corresponds to a global search technique in the search space of the optimization problem. Some of the terms related to this mode are:

Seeking Memory Pool (SMP): It is the number of copies of a cat produced in seeking mode.

Seeking Range of selected Dimension (SRD): It is the maximum difference between the new and old values in the dimension selected for mutation.

Counts of Dimension to Change (CDC): It is the number of dimensions to be mutated.

The steps involved in this mode are:

1. Create T copies of i^{th} cat.
2. Based on CDC update the position of each copy by randomly adding or subtracting SRD percents to the present position value.
3. Evaluate the fitness of all copies
4. Pick the best candidate from T copies and place it at the position of i^{th} cat.

3.1.2. Tracing mode

The tracing mode corresponds to a local search technique for the optimization problem. In this mode, the cat traces the target while spending high energy. The rapid chase of the cat is mathematically modeled as a large change in its position. Define position and velocity of i^{th} cat in the D-dimensional space as $X_{id} = (X_{i1}, X_{i2,}, ..., X_{iD})$ and $V_{id} = (V_{i1}, V_{i2,}, ..., V_{iD})$ where $d (1 \le d \le D)$ represents the dimension. The global best position of the cat swarm is represented as $P_{gd} = (P_{g1,} P_{g2}, ..., P_{gD})$. The updated equations are

$$V_{id} = W * V_{id} + c * r * (P_{gd} - X_{id}) \tag{6}$$

$$X_{id} = X_{id} + V_{id} \tag{7}$$

where W is the inertia weight, c is the acceleration constant and r is a random number uniformly distributed in the range [0, 1].

3.2. CSO Algorithm for Coordinated design of PSS and TCSC Damping Controllers

The CSO algorithm, the two major behavioral traits of cats is modeled as seeking mode and tracking mode which are combined to solve the optimization problem. To combine these two modes into the algorithm,

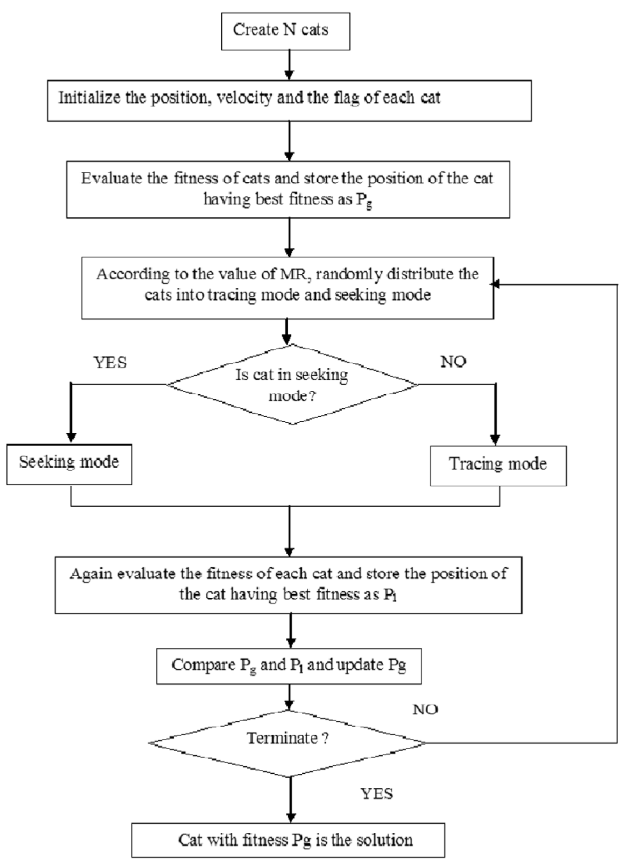

Figure 3: Flowchart of Cat Swarm Optimization Algorithm

mixture ratio (MR) is defined, which dictates the joining of seeking mode with tracing mode. Cats which are awake spend most of their time resting, observing their environment. If they decide to move while resting, the movement is done carefully and slowly. This behavior is represented in seeking mode. Tracing mode models the chasing of a target by the cat. Cats spend very little time chasing things as this leads to over use of energy resources. Hence to guarantee that the cats spend most of their time resting and observing i.e., most of the time is spent in seeking mode, MR is allocated a very small value.

The process of CSO algorithm is as follows.

1. Randomly initialize the position of cats in D-dimensional space for the population, i.e. X_{id}, representing position of i^{th} cat in d^{th} dimension.
2. Randomly initialize the velocity for cats, i.e. V_{id}.
3. Evaluate the fitness of each cat and store the position of the cat with best fitness as P_{gm} where m = 1, 2, . . . , D.
4. According to MR, cats are randomly picked from the population and their flag is set to seeking mode, and for others the flag is set to tracing mode.
5. If the flag of i^{th} cat is seeking mode, apply the cat to the seeking mode process, otherwise apply it to the tracing mode process. The steps of the corresponding modes are followed.
6. Evaluate the fitness of each cat and store the position of the cat with best fitness as P_{lm} where m = 1, 2, . . . , D.
7. Compare the fitness of P_g and P_l, and update P_g with smaller of P_g and P_l.
8. Check the termination condition (number of iterations or $P_g - P_l < \varepsilon$), if satisfied, terminate the program. Otherwise repeat steps 4–7.

4. SIMULATION RESULTS

Test System 1: WSCC 3-machine, 9-bus System

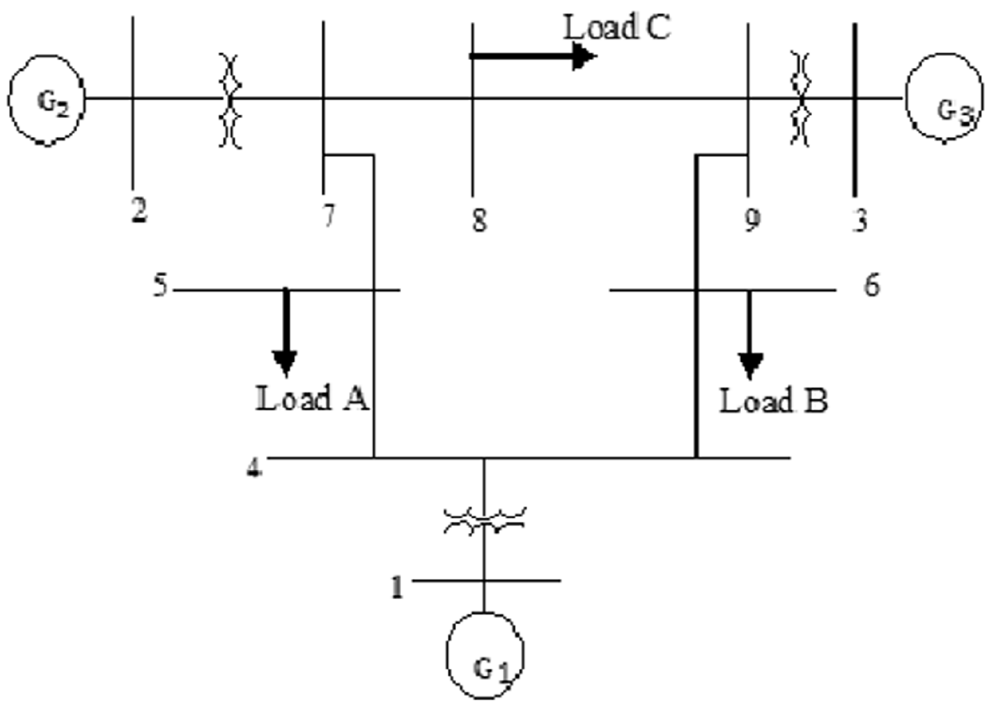

Figure 4: WSCC 3-machine, 9-bus system

The proposed technique is applied on WSCC 3-machine, 9-bus system shown in Fig. 4. Power flow, transmission line and dynamic data for the generators can be found in [16], and all generators are represented by fifth order model. For illustration and comparison purposes, it is assumed that all generators are equipped with PSS. The power flow in line 5–7 is the largest and therefore this line is considered as the best location for installing the TCSC controller in the system under study. The system generations and loading levels considered in this study are given in Table 1.

Table 2 shows the tuned parameters of PSS and TCSC obtained by BSO and CSO algorithms. Table 3 shows comparison of eigenvalues and damping ratios of electromechanical mode of oscillations using BSO and CSO based coordinated damping controllers at different loading levels. In all the three loading levels, CSO based coordinated controllers are giving better damping factors and better damping ratios compared to BSO based controllers. The corresponding values of damping ratios and damping factors are highlighted in this table. Using the proposed CSO based coordinated controllers, electromechanical mode eigenvalues are further shifted to the left half of s-plane and also damping ratios are also greater than that of BSO based damping controllers for all the loading conditions.

Table 1
Loadings and Generations in PU on system 100-MVA base

Load	*Light Load*		*Normal Load*		*Heavy Load*	
	P	*Q*	*P*	*Q*	*P*	*Q*
A	0.70	0.350	1.25	0.5	2.00	0.90
B	0.50	0.300	0.90	0.30	1.80	0.60
C	0.60	0.200	1.00	0.35	1.60	0.65
Local load at G1	0.60	0.200	1.00	0.35	1.60	0.65
Gen#	P	Q	P	Q	P	Q
G1	0.9649	0.2230	1.7164	0.6205	3.5730	1.8143
G2	1.0000	-0.1933	1.6300	0.0665	2.2000	0.7127
G3	0.4500	-0.2668	0.8500	-0.1086	1.3500	0.4313

Table 2
Tuned Parameters of Coordinated Controllers Using BSO and CSO

Gen#	*Tuned Parameters Using BSO[9]*			*Tuned Parameters Using CSO*		
	K	*T1*	*T2*	*K*	*T1*	*T2*
G1	23.0006	0.3282	0.0754	18.6753	0.6238	0.4842
G2	16.3196	0.1945	0.5846	2.4284	0.8745	0.1835
G3	3.8619	0.1177	0.7399	2.8422	0.6782	0.3985
TCSC	1.0958	0.8704	0.1741	5.8972	0.6746	0.2485

Table 3
Comparison of eigenvalues and damping ratios for different loadings

	Light Load	*Normal Load*	*Heavy Load*
Without controller	-10.60 ±11.48i, 0.6782 -0.95 ± 8.61i, 0.1103	-11.17 ±10.43i, 0.7307 -0.34 ± 8.81i, 0.0386	-11.35 ±11.28i, 0.7093 -0.15 ± 9.00i, 0.0167
BSOPSS+ BSOTCSC[9]	-4.51±7.38i, 0.5215 -1.09±0.71i, 0.8379	-4.15±8.15i, 0.4538 -1.04±0.84i, 0.7779	-4.49±7.77i, 0.5003 -1.03±0.86i, 0.7676
CSOPSS+ CSOTCSC	-9.50 ± 8.87i, 0.7307 -3.00 ± 4.23i, 0.5784	-10.36 ± 6.58i, 0.8441 -2.70± 4.27i, 0.5352	-10.54± 6.68i, 0.8446 -2.59± 4.25i, 0.5214

Test System 2: New England 10-machine, 39-bus system

The proposed method is applied on New England 10-machine, 39-bus system shown in Fig.5 for which power flow, transmission line and dynamic data for the generators can be found in [17]. All generators are represented by fifth order model, and are assumed to be equipped with PSS. To find the optimum location for TCSC, different locations are tested by residue method. Residues associated with critical mode are calculated using the transfer function between the TCSC active power deviation DP and degree of compensation DK_c (in p.u. of line reactance) are shown in Table 4. Line 26-29 has largest residue value and is therefore most effective location for placement of TCSC.

Table 4
Residues obtained using

Line	*Residue Value*
line 26-29	9.016
line 26-28	4.662
line 28-29	4.086
line 16-17	2.924
line 16-19	2.014
line 17-27	1.396
line 2-3	1.090
line 25-26	0.730
line 23-24	0.614
line 16-21	0.490
line 4-14	0.122
line 5-6	0.008
line 15-16	0.006

4.1. Eigenvalue Analysis

To assess the effectiveness and robustness of the proposed CSO based coordinated damping controllers, four different operating scenarios that represent the system under severe loading conditions and critical line outages are considered. These conditions are extremely hard from the stability point of view [18]. The different operating scenarios considered are given in Table 5.

Table 5
Operating Scenarios

Scenario	*Description*
Scenario 1	All lines in service
Scenario 2	Outage of line connecting bus no. 14 and 15
Scenario 3	Outage of line connecting bus no. 21 and 22
Scenario 4	Increase in generation of G7 by 25% and loads at buses 16 and 21 by 25%, with the outage of line 21–22

The tuned parameters of PSS and TCSC both for uncoordinated and coordinated design using proposed CSO are shown in the Table 6. The electromechanical modes and the damping ratios obtained for all the above cases without controller, uncoordinated CSO based TCSC (CSOTCSC), uncoordinated CSO based PSS (CSOPSS) and coordinated PSS and TCSC are given in Table 7.

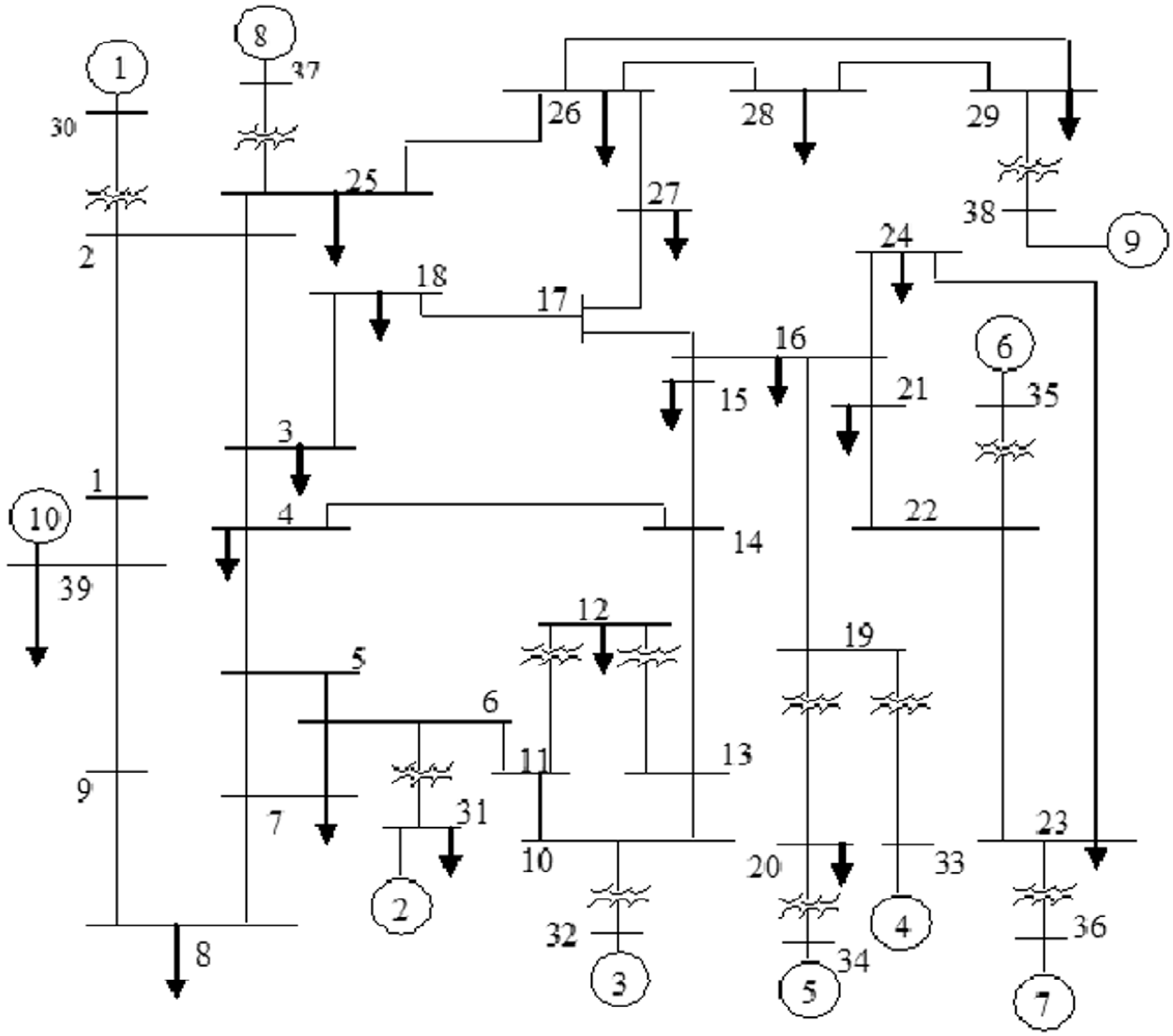

Figure 5: New England 10-machine, 39-bus System

Table 6
Tuned Parameters of Damping Controllers

Location	*Controller*	*Individual Design CSO*			*Coordinated Design CSO*		
		K	*T1*	*T2*	*K*	*T1*	*T2*
G1	PSS	29.1401	0.5100	0.3620	23.4301	0.5649	0.4652
G2	PSS	12.4885	0.7873	0.1153	18.4629	0.6333	0.1291
G3	PSS	3.4503	0.7753	0.1521	18.4872	0.5507	0.1855
G4	PSS	7.2830	0.6722	0.1656	12.9498	0.7350	0.1244
G5	PSS	23.4427	0.6210	0.1714	20.7443	0.4800	0.1914
G6	PSS	11.5024	0.6413	0.0721	5.8284	0.9101	0.0983
G7	PSS	22.6447	0.6222	0.1819	7.4601	0.6816	0.1288
G8	PSS	9.1202	0.6162	0.0859	4.7863	0.6355	0.0447
G9	PSS	11.6975	0.5636	0.1773	7.2442	0.7752	0.1591
G10	PSS	16.9927	0.9655	0.2247	39.2785	0.6834	0.1824
26-29	TCSC	24.86	0.6248	0.3885	46.74	0.5432	0.2677

Table 7
Comparison of eigenvalues and damping ratios for different scenarios

	No controller		*CSOTCSC*		*CSOPSS*		*CSOPSS+CSOTCSC*	
Scenario 1	-1.1878 ±10.6655i,	0.1107	-1.7668 ±12.0104i,	0.1455	-2.4162 +12.0605i,	0.1964	-2.4346 ±12.6585i,	0.1889
	-0.3646 ± 8.8216i,	0.0413	-1.3465 ±11.3821i,	0.1175	-1.9829 +10.8012i,	0.1806	-1.9286 ±11.2753i,	0.1686
	-0.3063 ± 8.5938i,	0.0356	-1.8658 ±11.0384i,	0.1667	-1.7019 + 9.9476i,	0.1686	-1.7789 ± 9.6962i,	0.1805
	-0.2718 ± 8.1709i,	0.0332	-1.1003 ± 9.0353i,	0.1209	-2.1133 + 8.0471i,	0.2540	-2.2539 ± 9.5881i,	0.2288
	-0.0625 ± 7.2968i,	0.0086	-0.5036 ± 8.5383i,	0.0589	-2.5967 + 6.1447i,	0.3893	-4.5930 ± 7.6273i,	0.5159
	-0.1060 ± 6.8725i,	0.0154	-1.1036 ± 7.4769i,	0.1460	-3.2019 + 5.7563i,	0.4861	-1.8027 ± 8.1302i,	0.2165
	0.2579 ± 6.1069i,	-0.0422	-0.1654 ± 7.3883i,	0.0224	-3.0043 + 5.1421i,	0.5045	-3.2273 ± 6.3264i,	0.4544
	0.0620 ±6.1767i,	-0.0100	-0.1381 ± 6.5183i,	0.0212	-1.7567 + 3.0258i,	0.5021	-2.4495 ± 3.7729i,	0.5445
	0.0794 ± 3.9665i,	-0.0200	-1.5368 ± 4.7261i,	0.3092	-1.6782 + 2.1050i,	0.6234	-2.1675 ± 3.5599i,	0.5201
Scenario 2	-1.1888 ±10.6603i,	0.1108	-1.3398 ±11.3718i,	0.1170	-2.5253 +12.0542i,	0.2050	-2.4590 ±12.6363i,	0.1910
	-0.3642 ± 8.8221i,	0.0412	-1.6994 ±11.6987i,	0.1438	-1.9901 +10.8087i,	0.1811	-1.9337 ±11.2157i,	0.1699
	-0.3087 ± 8.5753i,	0.0360	-1.8696 ±11.0315i,	0.1671	-1.7102 + 9.9943i,	0.1687	-4.6776 ± 7.6370i,	0.5223
	-0.2727 ± 8.1706i,	0.0334	-0.5195 ± 8.5374i,	0.0607	-1.9646 + 7.3887i,	0.2570	-1.7821 ± 9.6886i,	0.1809
	-0.0643 ± 7.2859i,	0.0088	-0.8693 ± 8.3003i,	0.1042	-2.6472 + 6.2266i,	0.3912	-2.1848 ± 9.4958i,	0.2242
	-0.1000 ± 6.7243i,	0.0149	-2.3575 ± 6.9503i,	0.3212	-3.2763 + 5.7046i,	0.4980	-1.7663 ± 8.1750i,	0.2112
	0.2997 ± 6.1030i,	-0.0490	-0.1678 ± 7.3889i,	0.0227	-3.0066 + 5.1781i,	0.5021	-2.7999 ± 6.1612i,	0.4137
	0.0824 ± 5.7423i ,	-0.0143	-0.1415 ± 6.5123i,	0.0217	-1.6607 + 2.8428i,	0.5044	-2.1681 ± 3.5588i,	0.5203
	0.0844 ± 3.8066i,	-0.0222	-1.3860 ± 5.6711i,	0.2374	-1.6896 + 2.0931i,	0.6281	-1.7187 + 1.5897i,	0.7341
Scenario 3	-1.1686 ±10.6268i,	0.1093	-1.7180 ±11.5697i,	0.1469	-2.4170 +11.9233i,	0.1987	-2.4931 ±12.6023i,	0.1941
	-0.3413 ± 8.7548i,	0.0390	-1.3331 ±11.3443i,	0.1167	-2.0174 +10.7464i,	0.1845	-1.9383 ±11.1536i,	0.1712
	-0.3013 ± 8.4738i,	0.0355	-1.8853 ±10.9565i,	0.1696	-1.6518 + 9.9336i,	0.1640	-1.7873 ± 9.6678i,	0.1818
	-0.2575 ± 8.0464i,	0.0320	-0.5176 ± 8.5059i,	0.0607	-1.9970 + 7.8928i,	0.2453	-2.1674 ± 9.4397i,	0.2238
	-0.0615 ± 7.3143i,	0.0084	-0.8127 ± 8.1625i,	0.0991	-3.1392 + 5.7681i,	0.4780	-4.6661 ± 7.6435i,	0.5211
	0.1283 ± 6.1862i,	-0.0207	-2.5740 ± 6.8505i,	0.3517	-2.3783 + 6.0489i,	0.3659	-1.7277 ± 8.1797i,	0.2067
	0.0427 ± 6.0556i,	-0.0070	-0.1642 ± 7.4097i,	0.0222	-3.0050 + 5.1556i,	0.5036	-2.8639 ± 6.1406i,	0.4227
	0.2018 ± 5.8565i,	-0.0344	-0.1394 ± 6.4985i,	0.0215	-1.7401 + 2.9982i,	0.5020	-2.4198 ± 3.7931i,	0.5378
	0.1659 ± 3.7438i,	-0.0443	-1.2972 ± 5.6493i,	0.2238	-1.7068 + 2.0800i,	0.6343	-2.1697 ± 3.5585i,	0.5206
Scenario 4	-1.1645 ±10.6163i,	0.1090	-1.6571 ±11.6273i,	0.1411	-2.4035 +11.8986i,	0.1980	-2.5045 ±12.5842i,	0.1952
	-0.3256 ± 8.8902i,	0.0366	-1.3292 ±11.3146i,	0.1167	-2.0364 +10.7212i,	0.1866	-1.9421 ±11.1032i,	0.1723
	-0.2977 ± 8.4483i,	0.0352	-1.8895 ±10.9189i,	0.1705	-1.6152 + 9.9467i,	0.1603	-1.7853 ± 9.6529i,	0.1819
	-0.2587 ± 8.0346i,	0.0322	-0.5186 ± 8.4896i,	0.0610	-1.9381 + 7.8659i,	0.2392	-2.1265 ± 9.4176i,	0.2203
	-0.0575 ± 7.3333i,	0.0078	-0.7591 ± 8.1011i,	0.0933	-3.1216 + 5.7626i,	0.4763	-4.6673 ± 7.6326i,	0.5217
	0.1557 ± 6.1630i,	-0.0253	-0.1602 ± 7.4295i,	0.0216	-2.3917 + 6.0340i,	0.3685	-1.7106 ± 8.2036i,	0.2041
	0.0586 ± 6.0959i,	-0.0096	-0.1385 ± 6.4878i,	0.0213	-1.7228 + 2.9184i,	0.5084	-2.9014 ± 6.1107i,	0.4289
	0.2089 ± 5.6778i,	-0.0368	-1.0325 ± 5.6786i,	0.1789	-1.9297 + 2.8567i,	0.5598	-2.4010 ± 3.8020i,	0.5339
	0.2352 ± 3.6446i,	-0.0644	-1.0592 ± 3.2019i,	0.3141	-1.7398 + 2.0732i,	0.6428	-2.1750 ± 3.5602i,	0.5213

From table 7, it is clear that the system with CSOTCSC is suffered from small damping factor (σ = -0.1381, -0.1415, -0.1394 and 0.385) for those operating scenarios. Further the proposed coordinated controllers shift substantially the electromechanical mode eigenvalues to the left of s-plane and the values of the damping factors with the proposed coordinated controllers are significantly improved (σ = -1.7789, -1.7187, -1.7277 and -1.7106). The damping ratios corresponding to coordinated controllers (ζ = 16.86%, 16.99%, 17.12% and 17.23%) are better than corresponding CSOTCSC values (ζ = 2.12%, 2.17%, 2.15% and 2.13%). Hence compared to the CSOTCSC and CSOPSS, the proposed coordinated controllers greatly enhance the system stability and improve the damping characteristics of electromechanical modes of oscillations.

The tuned parameters of PSS and TCSC both for coordinated design using GA, PSO, BSO and CSO are shown in the Table 8. The electromechanical mode eigenvalues and corresponding damping ratios obtained for all the above cases with GA, PSO and BSO based coordinated damping controllers are given in Table 9.

This table shows that with the proposed CSO based coordinated controllers, poorly damped electromechanical modes are further shifted to the left half of s-plane for all the scenarios. It is obvious that system damping is also significantly enhanced for these poorly damped modes with the proposed coordinated controllers.

Table 8
Tuned Parameters of Coordinated Damping Controllers using GA, PSO and BSO

Location	*Controller*	*Coordinated Design using GA*			*Coordinated Design using PSO*			*Coordinated Design using BSO*		
		K	*T1*	*T2*	*K*	*T1*	*T2*	*K*	*T1*	*T2*
G1	PSS	31.9574	0.6310	0.1497	39.7880	0.3987	0.1002	26.2845	0.6425	0.0428
G2	PSS	28.7563	0.8701	0.3906	40.7571	0.5737	0.2498	12.8566	0.6875	0.1893
G3	PSS	22.7592	0.6425	0.0773	38.0179	0.4186	0.1535	11.5556	0.6832	0.1882
G4	PSS	1.6534	0.9064	0.1895	2.3953	0.4098	0.0472	4.4392	0.6022	0.1996
G5	PSS	18.1713	0.5660	0.4651	10.7520	0.3448	0.2099	20.1588	0.5978	0.1254
G6	PSS	13.3569	0.9110	0.2405	46.4748	0.3338	0.1094	26.9422	0.8304	0.1688
G7	PSS	34.5109	0.6086	0.4676	20.6541	0.1998	0.1559	10.9898	0.6767	0.1012
G8	PSS	5.0671	0.6626	0.4008	26.0415	0.4246	0.2005	8.7575	0.8455	0.0345
G9	PSS	7.8578	0.9483	0.1722	29.8426	0.3096	0.1297	5.6288	0.8412	0.1869
G10	PSS	21.7755	0.6953	0.3175	29.9455	0.4498	0.1005	44.2864	0.9825	0.2124
26-29	TCSC	27.85	0.5692	0.3224	45.92	0.7438	0.3897	32.26	0.6132	0.2826

Table 9
Comparison of eigenvalues and damping ratios using GA, PSO, BSO and CSO based damping controllers

	GAPSS+GATCSC	*PSOPSS+PSOTCSC*	*BSOPSS+BSOTCSC*	*CSOPSS+CSOTCSC*
Scenario 1	-0.6917 ±12.6077i, 0.0548	-4.8532 ±11.8028i, 0.3803	-2.3285 ±11.1402i, 0.2046	-2.4346 ±12.6585i, 0.1889
	-0.6282 ±10.3659i, 0.0605	-1.4598 ±13.3108i, 0.1090	-1.6689 ±11.2509i, 0.1467	-1.9286 ±11.2753i, 0.1686
	-0.3535 ±10.4114i, 0.0339	-1.9942 ±12.7197i, 0.1549	-3.3852 ± 9.6463i, 0.3311	-1.7789 ± 9.6962i, 0.1805
	-0.6843 ± 9.3642i, 0.0729	-0.6765 ±11.6848i, 0.0578	-1.9386 ±10.0298i, 0.1898	-2.2539 ± 9.5881i, 0.2288
	-1.5065 ± 8.8559i, 0.1677	-0.9737 ± 9.3240i, 0.1039	-1.5313 ± 9.8321i, 0.1539	-4.5930 ± 7.6273i, 0.5159
	-0.8057 ± 6.7671i, 0.1182	-1.2737 ± 7.9850i, 0.1575	-2.8266 ± 5.1077i, 0.4842	-1.8027 ± 8.1302i, 0.2165
	-2.6875 ± 3.6331i, 0.5947	-1.2638 ± 6.1960i, 0.1999	-2.0861 ± 3.5333i, 0.5084	-3.2273 ± 6.3264i, 0.4544
	-1.7647 ± 3.5259i, 0.4476	-1.1928 ± 3.1623i, 0.3529	-1.3185 ± 2.2638i, 0.5033	-2.4495 ± 3.7729i, 0.5445
	-1.2692 ± 3.3035i, 0.3586	-1.7415 ± 2.4798i, 0.5747	-1.1487 ± 1.9274i, 0.5120	-2.1675 ± 3.5599i, 0.5201
Scenario 2	-0.5865 ±12.3722i, 0.0474	-4.8734 ±11.7816i, 0.3822	-2.3405 ±11.1349i, 0.2057	-2.4590 ±12.6363i, 0.1910
	-0.3850 ±10.4012i, 0.0370	-1.9831 ±12.6903i, 0.1544	-1.6689 ±11.2254i, 0.1471	-1.9337 ±11.2157i, 0.1699
	-0.8927 ± 9.8812i, 0.0900	-0.6899 ±11.6846i, 0.0589	-3.4003 ± 9.6539i, 0.3322	-4.6776 ± 7.6370i, 0.5223
	-0.7125 ± 9.1170i, 0.0779	-1.2828 ± 8.8452i, 0.1435	-1.9434 ± 9.9961i, 0.1908	-1.7821 ± 9.6886i, 0.1809
	-1.5979 ± 8.6491i, 0.1817	-1.3547 ± 7.9549i, 0.1679	-1.5289 ± 9.8135i, 0.1539	-2.1848 ± 9.4958i, 0.2242
	-0.7651 ± 6.7958i, 0.1119	-1.1571 ± 6.2555i, 0.1819	-2.7987 ± 5.0777i, 0.4827	-1.7663 ± 8.1750i, 0.2112
	-2.7483 ± 3.6108i, 0.6057	-1.1625 ± 3.0949i, 0.3516	-2.0324 ± 3.4491i, 0.5077	-2.7999 ± 6.1612i, 0.4137
	-1.7844 ± 3.5101i, 0.4532	-1.4811 ± 2.4881i, 0.5115	-1.3080 ± 2.2638i, 0.5003	-2.1681 ± 3.5588i, 0.5203
	-1.2582 ± 3.3098i, 0.3553	-2.4224 ± 2.1312i, 0.7508	-1.1594 ± 1.9260i, 0.5157	-1.7187 + 1.5897i, 0.7341
Scenario 3	-0.6360 ±12.2578i, 0.0518	-4.9889 ±11.7527i, 0.3907	-2.3441 ±11.1132i, 0.2064	-2.4931 ±12.6023i, 0.1941
	-0.3810 ±10.4071i, 0.0366	-1.5457 ±13.2553i, 0.1158	-1.6595 ±11.2000i, 0.1466	-1.9383 ±11.1536i, 0.1712
	-0.8428 ± 9.7069i, 0.0865	-2.0084 ±12.6366i, 0.1570	-3.4105 ± 9.6429i, 0.3334	-1.7873 ± 9.6678i, 0.1818
	-1.7062 ± 8.7588i, 0.1912	-0.6841 ±11.6994i, 0.0584	-1.9386 ± 9.9965i, 0.1904	-2.1674 ± 9.4397i, 0.2238
	-0.6920 ± 8.9882i, 0.0768	-1.2287 ± 8.6903i, 0.1400	-1.5210 ± 9.6288i, 0.1560	-4.6661 ± 7.6435i, 0.5211
	-0.7963 ± 6.7567i, 0.1170	-1.2983 ± 7.9971i, 0.1602	-2.7900 ± 5.0750i, 0.4818	-1.7277 ± 8.1797i, 0.2067
	-2.7473 ± 3.6285i, 0.6036	-1.1596 ± 6.1662i, 0.1848	-2.0127 ± 3.4595i, 0.5029	-2.8639 ± 6.1406i, 0.4227
	-1.7755 ± 3.5088i, 0.4515	-1.1415 ± 3.0901i, 0.3465	-1.2911 ± 2.2916i, 0.4909	-2.4198 ± 3.7931i, 0.5378
	-1.2371 ± 3.3201i, 0.3492	-1.4683 ± 2.4851i, 0.5087	-1.1791 ± 1.9282i, 0.5217	-2.1697 ± 3.5585i, 0.5206
Scenario 4	-0.5953 ±12.3048i, 0.0483	-5.0340 ±11.7321i, 0.3943	-2.3432 ±11.1040i, 0.2065	-2.5045 ±12.5842i, 0.1952
	-0.3729 ±10.4246i, 0.0358	-1.5578 ±13.2096i, 0.1171	-1.6481 ±11.1885i, 0.1457	-1.9421 ±11.1032i, 0.1723
	-0.8016 ± 9.6514i, 0.0828	-2.0517 ±12.5967i, 0.1608	-3.4226 ± 9.6344i, 0.3348	-1.7853 ± 9.6529i, 0.1819
	-1.8413 ± 8.9190i, 0.2022	-0.6783 ±11.7277i, 0.0577	-1.9439 ± 9.9893i, 0.1910	-2.1265 ± 9.4176i, 0.2203
	-0.6553 ± 8.9625i, 0.0729	-1.2247 ± 8.7873i, 0.1380	-1.4955 ± 9.5597i, 0.1546	-4.6673 ± 7.6326i, 0.5217
	-0.7609 ± 6.7577i, 0.1119	-1.2880 ± 8.0739i, 0.1575	-2.7877 ± 5.0874i, 0.4805	-1.7106 ± 8.2036i, 0.2041
	-2.7620 ± 3.6064i, 0.6080	-1.1051 ± 6.1810i, 0.1760	-1.6861 ± 2.9003i, 0.5026	-2.9014 ± 6.1107i, 0.4289
	-1.7828 ± 3.4965i, 0.4542	-1.1167 ± 3.0576i, 0.3431	-1.2812 ± 2.3054i, 0.4858	-2.4010 ± 3.8020i, 0.5339
	-1.2218 ± 3.3197i, 0.3454	-1.4048 ± 2.5248i, 0.4862	-1.1998 ± 1.9316i, 0.5277	-2.1750 ± 3.5602i, 0.5213

4.2. Nonlinear Time Domain Simulations

To investigate the robustness of the coordinated design of PSS and TCSC using Cat Swarm Optimization technique over a wide range of operating conditions and system configurations, nonlinear time domain simulation is carried out for the contingencies shown in Table 10. System performance is demonstrated by using the performance index, Integral of Time multiplied Absolute value of Error (*ITAE*), given by

$$PI = ITAE = \int_0^n t.(|\Delta\omega_1| + |\Delta\omega_2| + ... + |\Delta\omega_{10}|) \quad (8)$$

where "*n*" is the number of generators of that system. It is worth mentioning that the lower the value of this index is, better the system response in terms of time domain characteristics.

The system responses at critical generators for these contingencies with uncoordinated CSOTCSC, CSOPSS and with proposed coordinated CSO based PSS and TCSC damping controllers are shown in Figures 6, 7, 8 and 9 respectively. The performance index (*ITAE)* obtained for the above contingencies using these controllers are given the Table 10.

Table 10
Different contingencies considered for non-linear time domain simulations

Contingency	*Description*
Contingency (a)	A six-cycle three-phase fault, very close to the 14th bus in the line 4–14, which is cleared by tripping the line 4–14
Contingency (b)	A six-cycle fault disturbance at bus 33 at the end of line 19-33 with the load at bus-25 doubled and is cleared by tripping the line 19-33 with successful reclosure after 1.0 s.
Contingency (c)	A critical six cycle three-phase fault close to 22nd bus in the line 22–35 with load at 21st bus increased by 20% & load at 25th bus and is cleared by tripping the line 22-35 with successful reclosure after 1.0 s.
Contingency (d)	A six-cycle three-phase fault, near bus 14in the line 14–15 with 20% increase in load, which is cleared by tripping the line 14–15.

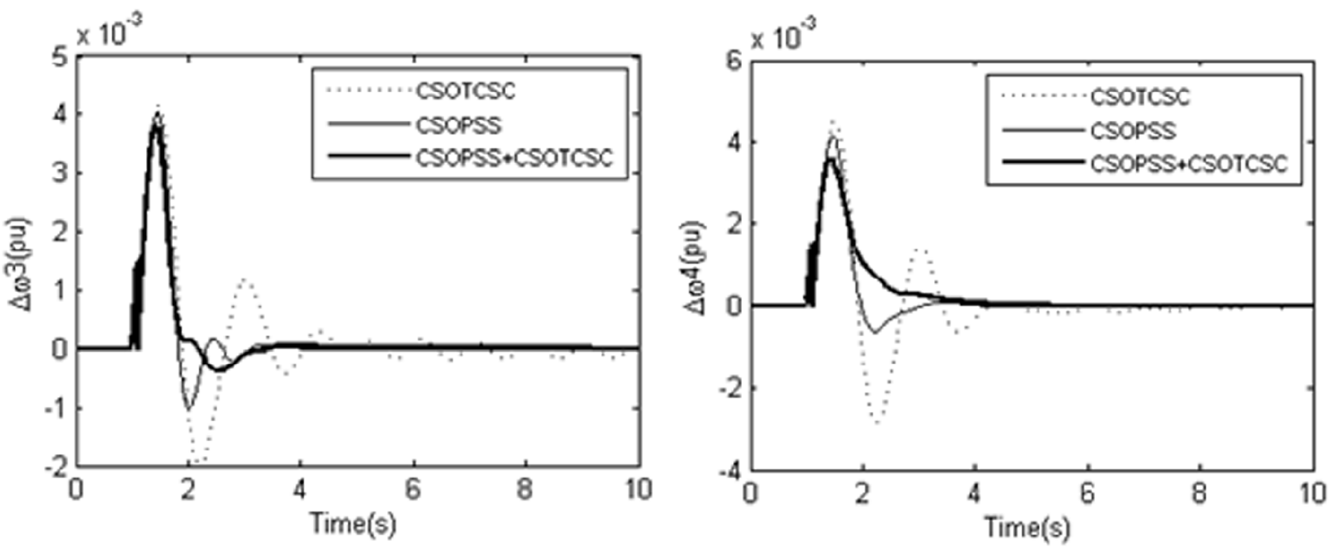

Figure 6: Speed deviations of 3rd and 4th generators for Contingency (a)

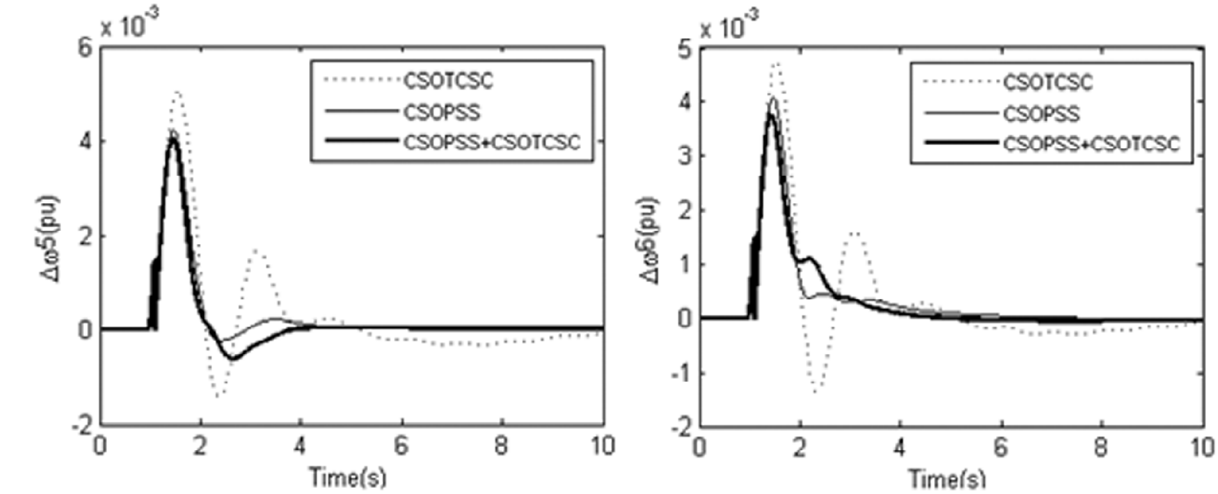

Figure 7: Speed deviations of 5th and 6th generators for Contingency (b)

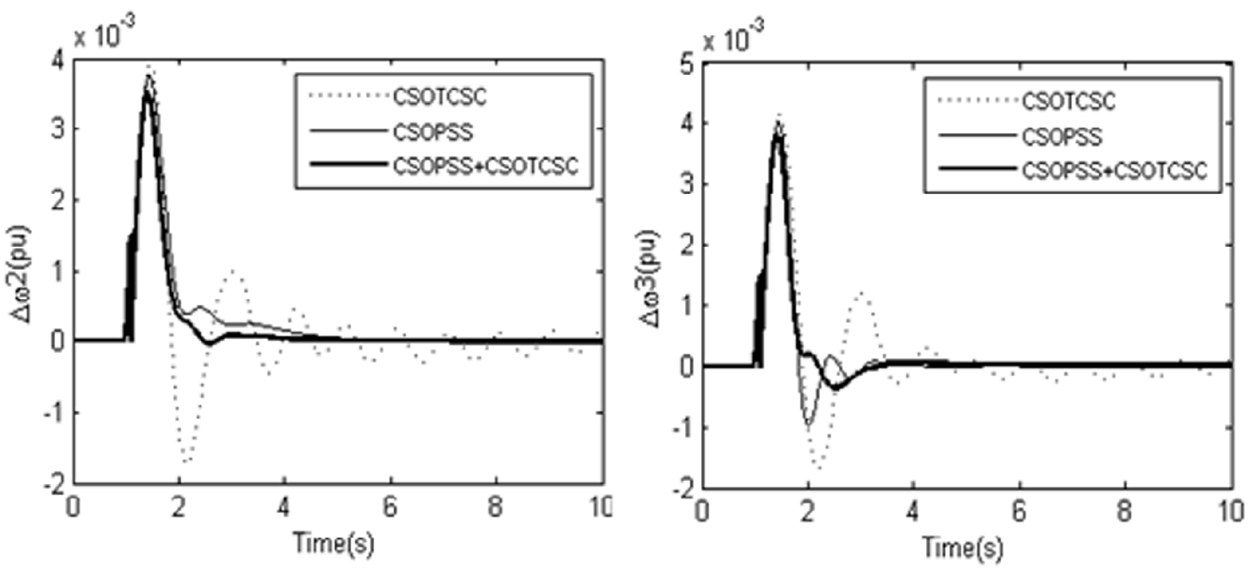

Figure 8: Speed deviations of 2nd and 3rd generators for Contingency (c)

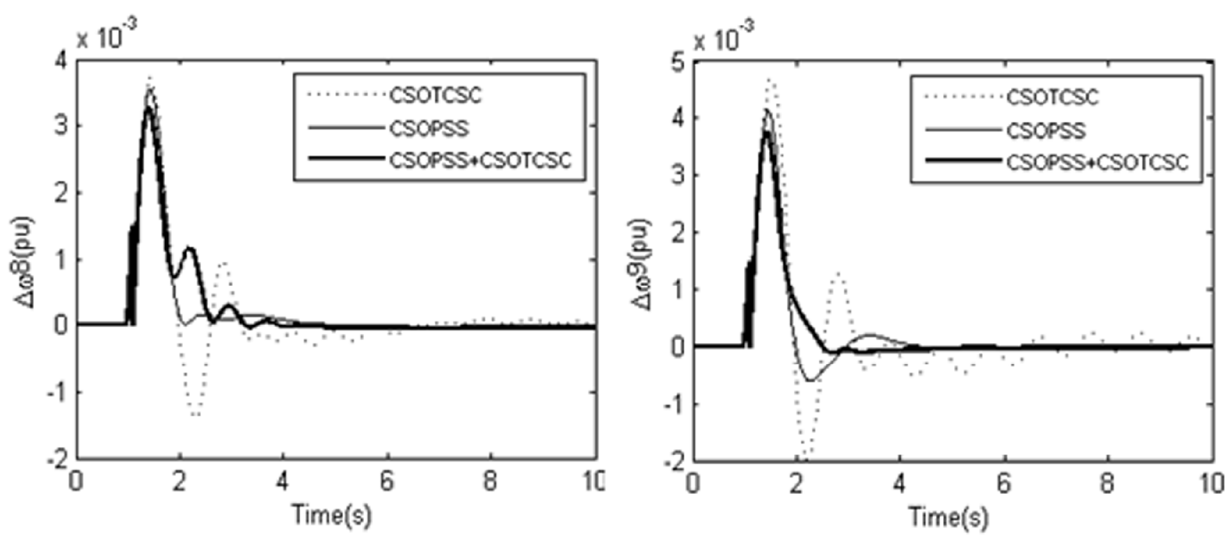

Figure 9: Speed deviations of 8th and 9th generators for Contingency (d)

It is clear from the figures that the system oscillations are well damped and the system returns to steady state much faster with CSO based coordinated controllers. Hence, the simulations results reveal the superiority of simultaneous coordinated design of the PSS and TCSC damping controller over uncoordinated damping controllers under different disturbances.

The performance index (*ITAE)* obtained for the above contingencies using GA, PSO, BSO & CSO based coordinated damping controllers are given the Table 12.

It is also clear from the above table that performance indices for CSO based coordinated damping controllers are less than the corresponding values of GA, PSO and BSO based coordinated damping controllers.

Table 11
Values of Performance Index for CSOTCSC, CSOPSS and Coordinated CSOPSS & CSOTCSC

	CSOTCSC	*CSOPSS*	*CSOPSS+CSOTCSC*
Contingency (a)	10.2292	4.8679	4.2093
Contingency(b)	10.3496	4.7085	4.3992
Contingency(c)	10.1829	4.7237	4.4478
Contingency(d)	9.8631	4.3503	4.3179

Table 12
Values of Performance Index for Coordinated GA, PSO, BSO and CSO based controllers

	GAPSS+ GATCSC	*PSOPSS+ PSOTCSC*	*BSOPSS+ BSOTCSC*	*CSOPSS+ CSOTCSC*
Contingency (a)	6.9713	6.6408	5.8846	4.2093
Contingency(b)	7.0013	6.6811	5.8078	4.3992
Contingency(c)	6.8893	6.5832	5.8019	4.4478
Contingency(d)	7.0203	6.5452	5.1858	4.3179

5. CONCLUSIONS

This paper presents a robust design algorithm for simultaneous coordinated tuning of PSS and TCSC damping controller in multi-machine power systems. The problem of tuning the PSS and TCSC damping controller parameters simultaneously, in order to enhance the damping of the power oscillations is formulated as a multi-objective optimization problem and CSO algorithm has been successfully applied to search for optimal controllers parameters.

The damping ratio and damping factors of electromechanical modes of oscillations obtained by using CSO algorithm on WSCC 3-machine, 9-bus system are found be superior compared to the results obtained using Bacterial Swarm Optimization (BSO) algorithm. The damping performance of PSS and TCSC controllers when they are designed independently using CSO is compared with coordinated design of PSS and TCSC with CSO algorithm on New England 10-machine, 39-bus system at different operating scenarios and contingencies. The eigenvalue analysis and nonlinear simulation results demonstrate the effectiveness and robustness of the proposed CSO based coordinated controllers over the Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Bacterial Swarm Optimization (BSO) based coordinated damping controllers.

6. APPENDIX

Parameters of Genetic Algorithm

Termination parameter, ε : 0.0001

Crossover probability, p_c: 0.8

Mutation probability, p_m: 0.05

Maximum number of iterations, t_{max} : 100

Parameters of Particle Swarm Optimization

Positive constants : C_1 = 2.4, C_2 = 1.6

Number of particles: 25

Maximum number of iterations, t_{max} : 100

Parameters of Bacterial Swarm Optimization

Number of dimensions of search space = 10

Number of bacteria = 6

Number of chemotactic steps = 6

Number of elimination and dispersal events = 2

Number of reproduction steps = 10

Probability of elimination and dispersal = 0.25

Parameters of Cat Swarm Optimization

Number of dimensions of search space = 10

Number of bacteria = 20

Mixed Ratio = 0.2

Seeking Memory Pool (SMP) = 5

Seeking Range of selected Dimension (SRD) = 40%

Counts of Dimension to Change (CDC) = 60%

Constants C1 = 2; R1=10 .

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