Cuckoo Search Approach for Optimal SVC Design in A Multimachine Power System

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Abstract: - In this paper, a new metaheuristic method, the Cuckoo Search (CS) approach, based on the life of a bird family is proposed for the optimal design of a Static Var Compensator (SVC) in a multimachine environment. The SVC parameter tuning problem is converted to an optimization problem which is solved by the CS approach. The performance of the proposed CS-based SVC (CSSVC) has been compared with Particle Swarm Optimization (PSO) based SVC (PSOSVC) under various operating conditions. The superiority of the suggested technique in damping oscillations and enhancing voltage profile over a wide range of operating conditions and system configurations is confirmed through eigenvalue, performance indices, and time domain simulation results over the PSO.

Key-Words: - Cuckoo Search Approach, PSO, SVC, Power System, Multimachine, Performance Indices.

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1 Introduction

The recent development of high-power electronics presents the use of Flexible AC Transmission Systems (FACTS) controllers in power systems, [1]. Subsequently, it has been demonstrated that variable shunt compensation is highly effective in both controlling power flow in the lines and hence the system voltage profile and stability, [2], [3]. The most popular type of FACTS device in terms of application is the SVC. This device is well known to improve power system properties such as steady state stability limits, voltage regulation and var compensation, dynamic over-voltage and under-voltage control, and damp power system oscillations. The SVC is an electric generator that dynamically controls the flow of power through a variable reactive admittance to the transmission grid, [4], [5], [6].

In the last few years, many researchers have suggested techniques for designing SVC to enhance the damping of electromechanical oscillations of power systems and improve power systems' stability. A robust control theory in designing an SVC controller to damp out power system swing modes is presented in, [7]. An adaptive network-based fuzzy inference system (ANFIS) for SVC is illustrated in, [8], to improve the damping of power systems. A multi-input, single-output fuzzy neural network is developed in, [9], for voltage stability evaluation of the power systems with SVC. A method of determining the location of an SVC to improve the stability of the power system is suggested in, [10]. A systematic approach for designing an SVC controller, based on wide area signals, to improve the damping of power system oscillations is presented in, [11]. The Genetic Approach (GA) optimization technique is employed for the simultaneous tuning of a PSS and an SVC-based controller, [12]. A state estimation problem of power systems incorporating various FACTS devices is addressed in, [13]. A novel hybrid method for the simulation of power systems equipped with SVC is suggested in, [14]. The design of SVC with delayed input signal using a state space model based on the Pade approximation method is presented in, [15]. A new optimization approach known as Bacterial Foraging (BF) for designing SVC to damp power system electromechanical oscillations for single machine infinite bus system and multimachine system is introduced in, [16], [17]. An application of probabilistic theory to the coordinated design of PSSs and SVC is employed in, [18]. The application of the decentralized modal control method for pole placement in power systems utilizing FACTS devices was developed in, [19]. The parameter tuning of the SVC-based flower approach is illustrated in, [20]. Imperialist Competitive Approach (ICA) is presented in, [21], for SVC design.

Several optimization techniques have been adopted to solve a variety of engineering problems in the past decade. GA has attracted attention in the field of SVC optimization, [22]. Although GA is very satisfactory in finding global or near-global optimal results of the problem; it needs a very long run time that may be several minutes or even several hours depending on the size of the system under study. Moreover swarming strategies in bird flocking and fish schooling are used in the PSO, [23], [24]. However, PSO suffers from partial optimism, which causes the less exact regulation of its speed and direction. Also, this approach cannot work out the problems of scattering. In addition, the approach suffers from slow convergence in the refined search stage, and weak local search ability, and the approach may lead to possible entrapment in local minimum solutions.

A new metaheuristic approach known as the CS approach, based on the life of a bird family, is proposed in this paper for the optimal design of SVC parameters. The problem of a robust SVC design is formulated as an objective optimization problem and the CS approach is used to handle it. The effectiveness of the proposed CSSVC is tested on a multimachine power system under various operating conditions in comparison with PSOSVC via time domain analysis, eigenvalue, and some performance indices. Results evaluation show that the suggested approach attains good robust performance for suppressing the low-frequency oscillations under various operating conditions and disturbances.

2 Problem Formulation

2.1 Power System Model

Generally, a power system can be established by a group of nonlinear differential equations as:

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

Where X and U are the vectors of the state variables and of input variables. In this study, $\mathrm{X} = [\delta, \omega, E'_q, E_{fd}, V_f]^T$ and U is the output of SVC. E'_q, E_{fd} and V_f are the internal, field, and excitation voltages respectively. Also, δ and ω are the rotor angle and speed, respectively.

2.2 SVC Structure

The thyristor-controlled reactor (TCR) in parallel with a fixed capacitor bank shown in Figure 1, is used to develop the desired SVC model. The system is then shunt connected to the AC system through a setup transformer to bring the voltages up to the required transmission levels, [8]. It is obvious from (2) and Figure 2, that if the firing angle α of the thyristors is controlled; SVC can control the bus voltage magnitude. The time constant (T_r) and gain (K_r) represent the thyristor's firing control system. The SVC parameters are given in the Appendix.

$$\dot{B}_e = \frac{1}{T_r}\left[-B_e + K_r(V_{ref} - V_t + V_s)\right] \tag{2}$$

The variable effective susceptance of the TCR is given by

$$B_V = -\frac{(2\pi - 2\alpha + \sin 2\alpha)}{\pi X_L} \quad \pi/2 \le \alpha \le \pi \tag{3}$$

Where X_L is the reactance of the fixed inductor of SVC. The effective reactance is

$$X_e = X_C \frac{\pi / r_X}{\sin 2\alpha - 2\alpha + \pi(2 - 1/r_X)} \tag{4}$$

Where X_e=-1/B_e and $r_X = X_e / X_L$.

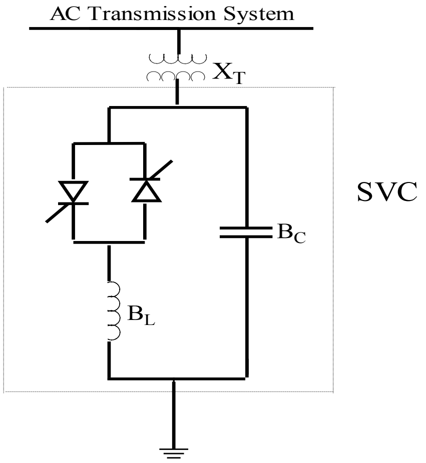

Fig. 1: SVC equivalent circuit.

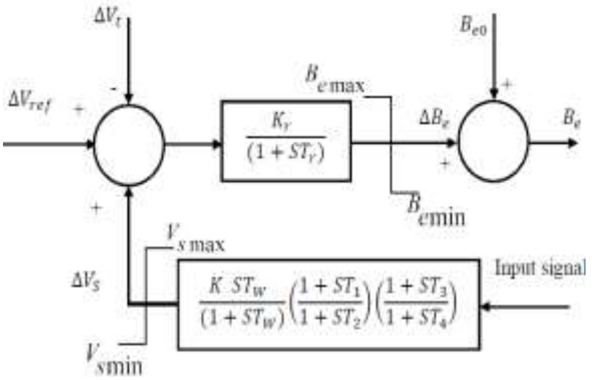

Fig. 2: Block diagram of SVC.

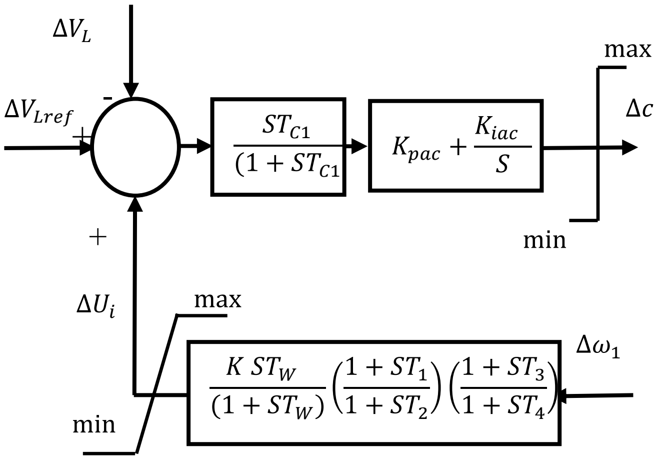

Fig. 3. Block diagram of AC voltage regulator with a supplementary damping signal.

An auxiliary stabilizing signal from speed can be imposed on the SVC control loop. The block diagram of an SVC with the auxiliary stabilizing signal is shown in Figure 3. This controller may be considered a lead-lag compensator. It comprises a gain block, limiter, signal washout block, and two stages of the lead-lag compensator. The parameters of the damping controllers for simultaneous coordinated design are obtained using the CS approach.

2.3 Test System

A multimachine system that consists of three generators and nine buses is considered here. The system data and loading events are given in, [16], [17]. Bus number 5 will be considered here as the best location for installing the SVC controller, [20].

3 Cuckoo Search Approach

The breeding behavior of cuckoo species and the basic items of the proposed approach are discussed below.

- ***Cuckoo Breeding Behavior***

CS is a metaheuristic search approach that has been introduced recently by, [25]. This approach is inspired by the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds, which may be of different species. At the appropriate moment, the hen cuckoo flies down to the host's nest, pushes one egg out of the nest, lays an egg, and flies off. The whole process takes about 10 seconds. A female may visit up to 50 nests during a breeding season. The host birds may detect that the eggs are not their own and either throw them away or abandon the nest and build new ones elsewhere. This has resulted in the evolution of cuckoo eggs which mimic the eggs of local host birds, [26]. Moreover, the timing of egg laying of some species is also amazing. Parasitic cuckoos often select a nest where the host bird just lays its eggs. In general, the cuckoo eggs hatch slightly earlier than their host eggs. It methodically dislodges all host progeny from host nests. It is a much larger bird than its hosts and needs to monopolize the food supplied by the parents. The chick will roll the other eggs out of the nest by pushing them with its back over the edge. If the host's eggs hatch before the cuckoos, the cuckoo chick will push the other chicks out of the nest in a similar way.

- ***Lévy Flights***

The use of Lévy flights for both local and global searching is an important component of the CS, [27]. The Lévy flight process is a random walk that is characterized by a series of instantaneous jumps selected from a probability density function which has a power law tail. This process represents the optimum random search pattern and is frequently found in nature. When generating a new egg, a Lévy flight is done starting at the location of a randomly chosen egg, if the objective function value at these new coordinates is better than another randomly chosen egg then that egg is shifted to this new location. One of the advantages of CS over other optimization approaches is that only one parameter, the fraction of nests to abandon P_a, needs to be adjusted. The use of Lévy flights as the search method means that the CS can simultaneously find all optima in a design space and the method has been shown to perform well in comparison with other approaches, [28].

- ***Cuckoo Search Implementation***

Each egg in a nest performs a solution, and a cuckoo egg introduces a new solution. The target is to use the new and potentially better solutions to replace a not-so-good solution in the nests. Each nest has one egg for a simple case. The approach can be developed for more sophisticated cases in which each nest has multiple eggs representing a set of solutions. To apply this search as an optimization approach, three below presented approximation rules, [25], [26]:

1-Cuckoos select a random nest for laying their eggs. Artificial cuckoos can lay only one egg at a time.

2- The elitist selection process is applied, so only the eggs with the highest quality are passed to the next generation.

3- The number of available host nests is specified and a host can detect a foreign egg with a probability $P_a \in [0,1]$. If a cuckoo egg is discovered by the host, it may be thrown away, or the host may abandon its own nest and commit it to the cuckoo intruder.

The last assumption can be approximated by a factor P_a of the n nests being exchanged by new nests. The quality of a solution is relative to the objective function of a maximization problem. Based on these three rules, the flow chart of CS is shown in Figure 4. The parameters of CS are shown in the appendix.

When generating new solutions x_i^{t+1} for the i^{th} cuckoo, a Lévy flights is carried out

$$x_i^{t+1} = x_i^t + \alpha \oplus \text{Lévy}(\lambda) \tag{5}$$

Where $\alpha > 0$ is the step size which should be proportional to the scales of the optimization problem. The product $\oplus$ means an entrywise walk during multiplications. Lévy flights essentially provide a random walk while their random steps are drawn from a Lévy distribution for large steps.

$$\text{Lévy} \sim u = t^{-\lambda}, \ (1 < \lambda \leq 3) \tag{6}$$

Which has an infinite variance with an infinite mean. Here the steps essentially form a random walk process with a power law step-length distribution with a heavy tail. Some of the new solutions should be generated by Lévy walking around the best solution obtained so far, this will speed up the local search. However, a substantial fraction of the new solutions should be generated by far-field randomization and whose locations should be far enough from the current best solution, this will make sure the system will not be trapped in a local optimum.

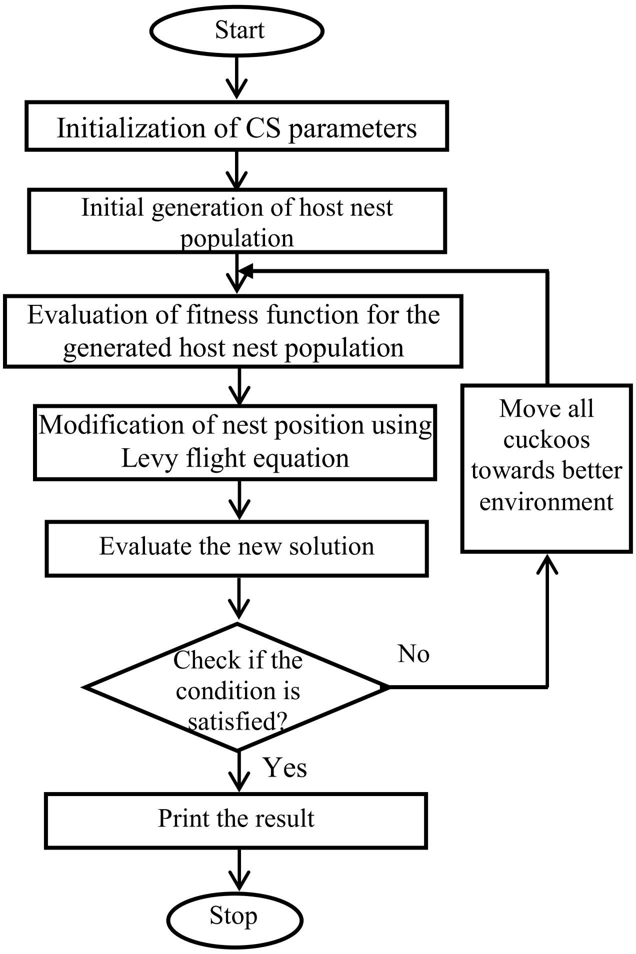

Fig. 4: Flowchart of cuckoo approach.

4 Objective Function

An Integral Time Absolute Error (ITAE) of the speed deviation of a generator is considered as the proposed objective function. It can be written as:

$$J = \int_0^{t_{sim}} t\left\{\left|\Delta\omega_{12}\right| + \left|\Delta\omega_{23}\right| + \left|\Delta\omega_{13}\right|\right\} dt \tag{7}$$

The lower and upper limits of the stabilizer gain are [1- 100]. Also, these limits are [0.06 -1.0] for T_{1i} and T_{3i}. Other time constants T_{2i} and T_{4i} are fixed at 0.05 second. CS searches for the optimal parameters of SVC to enhance the damping behavior and reduce the overshoot and settling time of the system response.

5 Results and Analysis

In this section, the superiority of the suggested CS approach in designing SVC compared with PSO is illustrated. Table 1, shows the system eigenvalues, and damping ratio of mechanical mode with three different loading conditions. It is clear that the CSSVC shifts the electromechanical mode eigenvalues to the left of the S-plane and the values of the damping factors with the proposed CSSVC are significantly enhanced to be (σ=-0.64,-0.76,-0.98) for light, normal, and heavy loading respectively. Also, the damping ratios corresponding to CSSVC controllers are larger than those corresponding to PSOSVC. Hence, compared with PSOSVC, CSSVC provides good robust performance and achieves superior damping characteristics of electromechanical modes. Results of CSSVC parameters set values based on the proposed objective function using CS and PSO are given in Table 2.

Table 1. Mechanical modes and ζ under different loading conditions and controllers.

	PSOSVC	CSSVC
Light load	−1.95±8.55j, 0.22	−4.08±9.02j, 0.41
	−3.16±8.34j, 0.36	−3.99±7.94j, 0.45
	−0.41±0.95j, 0.41	−0.64±0.84j, 0.61
Normal load	−2.12±10.66j, 0.2	−4.38±11.05j, 0.37
	−1.95±7.21j, 0.26	−3.14±8.96j, 0.33
	−0.45±0.85j, 0.49	−0.76±0.73j, 0.72
Heavy load	−1.84±11.45j, 0.16	−4.07±11.4j, 0.34
	−1.12±6.88j, 0.16	−2.48±8.71j, 0.27
	−0.52±0.96j, 0.5	−0.98±0.70j, 0.81

Table 2. Optimal SVC parameters for various approaches

Parameters	PSO	CS
K	73.6102	79.4
T_1	0.7601	0.2658
T_3	0.9014	0.4703

5.1 Response Under Normal Load Condition

The validation of the system performance due to a 20% increase in mechanical torque of generator 1 as a small disturbance is verified. Figure 5 and Figure 6, show the response of $\Delta\omega_{13}$, and $\Delta\omega_{12}$ due to this disturbance under normal loading conditions. It can be seen that the system with the proposed CSSVC is more stabilized than PSOSVC. In addition, the required mean settling time to mitigate system oscillations is approximately 2.22 seconds with CSSVC, and 2.89 seconds for PSOSVC so the designed controller is qualified for supplying adequate damping to the low-frequency oscillations.

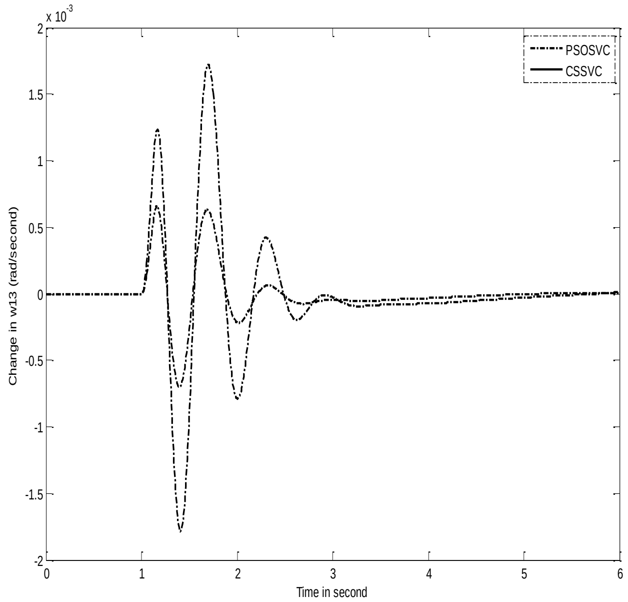

Fig. 5: Change of $\Delta\omega_{13}$ for normal condition.

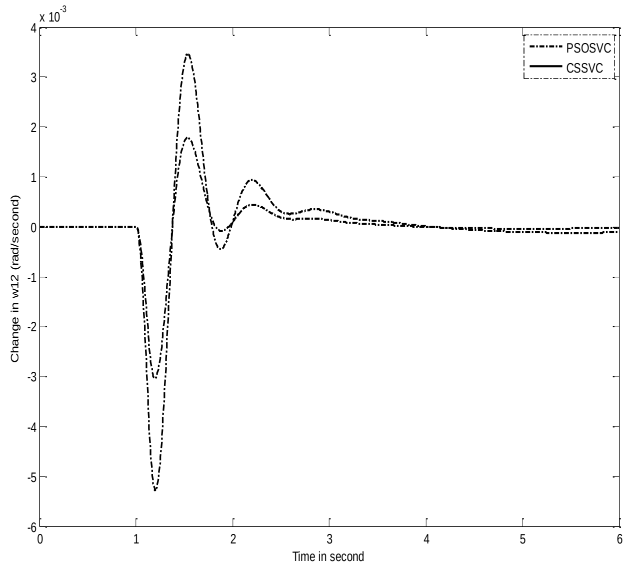

Fig. 6: Change of $\Delta\omega_{12}$ for normal load.

5.2 Response Under Heavy Load Conditions

Figure 7 and Figure 8, show the system response under heavy loading conditions. These figures indicate the superiority of the CSSVC in reducing the settling time and suppressing power system oscillations. Moreover, the mean settling times of these oscillations are 2.2, and 2.81 seconds for CSSVC, and PSOSVC respectively. Hence, the CSSVC controller greatly improves the system stability and enhances the damping characteristics of the power system. Furthermore, the settling time of the proposed controller is smaller than that in, [16].

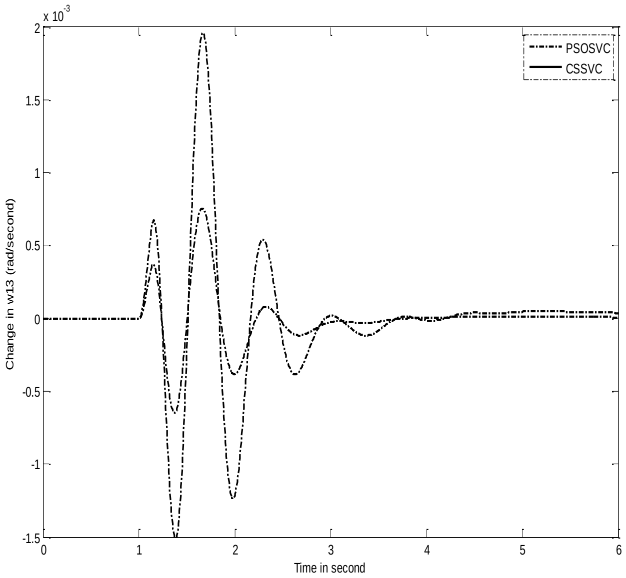

Fig. 7: Change of $\Delta\omega_{12}$ for heavy condition.

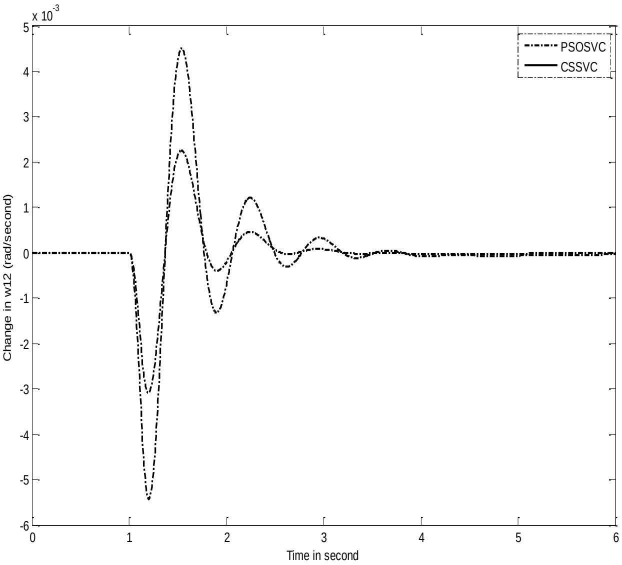

Fig. 8: Change of $\Delta\omega_{13}$ for heavy condition.

5.3 Robustness and Performance Indices

To demonstrate the robustness of the proposed controller, some performance indices: the Integral of the Absolute value of the Error (IAE), and the Integral of the Time multiplied Absolute value of the Error (ITAE), are being used:

$$IAE = \int_{0}^{\infty} \left(\left|\Delta w_{12}\right| + \left|\Delta w_{23}\right| + \left|\Delta w_{13}\right| \right) dt \qquad (8)$$

$$ITAE = \int_{0}^{\infty} t \left(\left|\Delta w_{12}\right| + \left|\Delta w_{23}\right| + \left|\Delta w_{13}\right| \right) dt \qquad (9)$$

It is noteworthy that the lower the value of these indices is, the better the system response in terms of time domain characteristics. Numerical results of performance robustness for all cases are listed in Table 3. It can be seen that the values of this system's performance with the CSSVC are smaller compared with those of PSOSVC and open loop. This demonstrates that the overshoot, settling time, and speed deviations of all units are greatly decreased by applying the proposed CS-based tuned SVC. Eventually; the values of these indices are smaller than those obtained in, [20].

Table. 3. Indices for various approaches.

	$IAE*10^{-4}$		$ITAE*10^{-4}$	
	PSOSVC	CSSVC	PSOSVC	CSSVC
Light load	5.91	4.13	12.62	6.48
Normal load	10.72	8.82	35.38	33.07
Heavy load	12.81	10.3	40.94	37.9

6 Conclusions

A new optimization approach known as the CS approach, for optimal designing of SVC parameters, is proposed in this paper. The SVC parameter tuning problem is formulated as an optimization problem and the CS approach is employed to seek optimal parameters. The stability performance of the system is improved by minimizing the time-domain objective function. Simulation results confirm the robustness and superiority of the proposed controller in providing good damping characteristics to system oscillations over a wide range of loading conditions. Moreover, the system performance characteristics in terms of the 'IAE' and 'ITAE' indices reveal that the proposed CSSVC demonstrates its effectiveness more than PSOSVC.

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APPENDIX

a) The parameters of the CS approach are as follows: Max generation=100; Number of nests=50; P_a =0.25.
b) The parameters of PSO are as follows: Max generation=100; No. of Population in swarm = 50; C_1=2; C_2=2, w = 0.9.
c) SVC Controller: Tr = .015 second; α_0 = 140; Kr = 50; T_2= .05 second; T_4 = .05 second; T_W = 10 second, X_T = .08 p.u.

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The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.