Research Article

Hybridized Symbiotic Organism Search Algorithm for the Optimal Operation of Directional Overcurrent Relays

Muhammad Sulaiman [ID], Ashfaq Ahmad, Asfandyar Khan [ID], and Shakoor Muhammad

Department of Mathematics, Abdul Wali Khan University Mardan, Mardan, Pakistan

Correspondence should be addressed to Muhammad Sulaiman; sulaiman513@yahoo.co.uk

This paper presents the solution of directional overcurrent relay (DOCR) problems using Simulated Annealing based Symbiotic Organism Search (SASOS). The objective function of the problem is to minimize the sum of the operating times of all primary relays. The DOCR problem is nonlinear and highly constrained with two types of decision variables, namely, the time dial settings (TDS) and plug setting (PS). In this paper, three models of the problem are considered, the IEEE 3-bus, 4-bus, and 6-bus, respectively. We have applied SASOS to solve the problem and the obtained results are compared with other algorithms available in the literature.

1. Introduction

Due to rapidly growing power systems, the stability and security issues are highly important for the power system researchers [1–3]. The protection systems are mainly used to detect and clear faults as fast and selective as possible [4–6]. The protection relays are used for detecting the faults in the system and to detach the faulty parts from the system in real time. Proper coordination of relays is essential to maintain the appropriate operation of the overall protection system. There are various types of relays with different operating principles. An example of these relays, which are used as a good technical tool for the protection of power systems, is directional overcurrent relay [7–9]. Such a relay is divided into two units, that is, the instantaneous unit and the time overcurrent unit. The parameters to be defined in the overcurrent unit are the time dial settings (TDS) and the plug settings (PS). Computers have made the huge calculations in DOCR problems in power systems easy [10, 11]. Different optimization algorithms are used to solve the relays coordination problems in which the objective function is to minimize activity time of all main relays. The constraints of this optimization problem are considered in the second layer of relay, which should respond, if the main layer of relay fails

to operate on nearby fault. This depends on the variables, TDS, PS, and the minimized working time of relay. There is a nonlinear relationship between the operating time of overcurrent relays, TDS, and PS.

In electrical engineering, the power system engineering has the longest history among all other areas. Ever since, different numerical optimization techniques have been applied to power systems engineering and played an important role [12]. Optimization problems are usually nonlinear, which have nonlinear objective functions and constraints [13, 14].

Nowadays, researchers use different optimization algorithms to find the optimal solutions for the problems of relays settings and coordination. Examples of these optimization algorithms are Evolutionary Algorithm (EA) [15], Differential Evolution (DE) [16], Modified Differential Evolution (MDE) [17], Self-Adaptive Differential Evolutionary (SADE) [18], Particle Swarm Optimization (PSO) [19], Modified Particle Swarm Optimizer [20, 21], Evolutionary Particle Swarm Optimization (EPSO) [22], Box-Muller Harmony Search (BMHS) [23], Zero-One Integer Programming (ZOIP) approach [24, 25], Covariance Matrix Adaptation Evolution Strategy (CMA-ES) [26], Seeker Algorithm [27], Chaotic Differential Evolution Algorithm (CDEA) [28], Adaptive Differential Evolution [29], Artificial Bee Colony (ABC) [30], Firefly

Optimization Algorithm (FOA) [31], Modified Swarm Firefly Algorithm (MSFA) [32], and Biogeography Based Optimization (BBO) [33]. BFOA has been applied to obtain the optimal location and size of multiple distributed generators (DG) [34], optimal placement and sizing of DG [35], power system harmonics estimation [36], distribution systems reconfiguration for loss minimization [37], minimum load balancing index for distribution system [38], power system stabilizer for the suppression of oscillations [39], and optimum economic load dispatch [40].

During the last few years, PSO algorithm has been applied for Optimal Power Flow (OPF) control in power systems [41], OPF problem with FACTS devices [42], economic dispatch problems [43], optimal sizing and placement of DG [44], optimal location and sizing of static synchronous series compensator [45], and optimized controller design of energy storage devices [45, 46].

This paper proposes the use of a hybrid optimization technique—namely, Simulated Annealing based Symbiotic Organism Search (SASOS) [1, 47]—to find the optimal solutions for the relays settings. This algorithm is applied to different models of the DOCR problems such as the IEEE 3-bus, 4-bus, and 6-bus models. To check the efficiency of the proposed algorithm for the three cases, we have minimized the total activity time (T) for each relay.

2. Problem Formulation

There are two important settings in each overcurrent relay for its satisfactory operations. The time dial settings (TDS) represent the activation time of each relay and the relay operation is decided by the plug settings (PS). The plug settings (PS) depend on the maximum load current and fault current due to short circuit. The main factors which control the total operating time of the relay are TDS and PS, and the fault current is represented by I_f [15, 22], where

$$T = \frac{\alpha \times \text{TDS}}{\left(I_f / \left(\text{PS} \times \text{CT}_{\text{pri-rating}}\right)\right)^{\beta} - \gamma}, \tag{1}$$

where I_f denotes the fault current at the current transformer (CT) initial terminal and $\text{CT}_{\text{pri-rating}}$ is the primary rating of CT. Constants α, β, and γ are assigned values 0.14, 0.02, and 1.0, respectively, and that is according to IEEE standards [26].

The current, seen by the relay, denoted by I_{relay}, is equal to the ratio between I_f and $\text{CT}_{\text{pri-rating}}$, which is a nonlinear equation:

$$I_{\text{relay}} = \frac{I_f}{\text{CT}_{\text{pri-rating}}}. \tag{2}$$

2.1. Objective Function. In coordination studies [22], the main objective is to minimize the total time taken in operation of primary relays for clearing a fault. The objective function takes the following form:

$$F = \sum_{i=1}^{N_{\text{cl}}} T_{\text{pri-cl-in}}^i + \sum_{j=1}^{N_{\text{far}}} T_{\text{pri-far-bus}}^j, \tag{3}$$

where

$$T_{\text{pri-cl-in}}^i = \frac{0.14 \times \text{TDS}^i}{\left(I_f^i / \left(\text{PS}^i \times \text{CT}_{\text{pri-rating}}^i\right)\right)^{0.02} - 1},$$

$$T_{\text{pri-far-bus}}^j = \frac{0.14 \times \text{TDS}^j}{\left(I_f^j / \left(\text{PS}^j \times \text{CT}_{\text{pri-rating}}^j\right)\right)^{0.02} - 1}, \tag{4}$$

where $T_{\text{pri-cl-in}}$ is the relay operation time to clear a near-end fault while $T_{\text{pri-far-bus}}$ is its operation time in case of a far end fault. N_{cl} and N_{far} represent the relays fixed at the ends of the front line.

2.2. Constraints. The objective function is bound to the three constraints related to TDS, PS, and I_f.

Equation (5) represents the bound constraints on TDS:

$$\text{TDS}_i^{\text{min}} \leq \text{TDS}_i \leq \text{TDS}_i^{\text{max}}. \tag{5}$$

$\text{TDS}_i^{\text{min}}$ and $\text{TDS}_i^{\text{max}}$ are the lower and upper bounds for TDS, whose values are given by 0.05 and 1.1, respectively, while i varies from 1 to N_{cl}.

The second constraint is PS of the relay that takes the following form:

$$\text{PS}_i^{\text{min}} \leq \text{PS}_i \leq \text{PS}_i^{\text{max}}. \tag{6}$$

PS_i^{min} and PS_i^{max} are the lower and upper bounds of PS, whose values are given by 1.25 and 1.50, respectively, while i varies from 1 to N_{far}.

The third constraint is related to the fault current and pickup current. The operating time of relay depends on the type of relay. According to [24, 33], the operating time of relay is defined by

$$T_i^{\text{min}} \leq T_i \leq T_i^{\text{max}}. \tag{7}$$

T_i^{min} and T_i^{max} are the lower and upper bounds for relay functioning time, whose values are adopted as 0.05 and 1, respectively.

During the optimization procedure, the time taken by primary relays to coordinate with the backup relays is constrained as in

$$T^{\text{backup}} - T^{\text{primary}} \geq \text{CTI}, \tag{8}$$

where CTI represents the specified coordination time.

T^{backup} and T^{primary} represent the working time of primary and backup relays, which can be obtained using the following equations:

$$T_i^{\text{backup}} = \frac{0.14 \times \text{TDS}^x}{\left(I_f^i / \left(\text{PS}^x \times \text{CT}_{\text{pri-rating}}^i\right)\right)^{0.02} - 1},$$

$$T_i^{\text{primary}} = \frac{0.14 \times \text{TDS}^y}{\left(I_f^i / \left(\text{PS}^y \times \text{CT}_{\text{pri-rating}}^i\right)\right)^{0.02} - 1}. \tag{9}$$
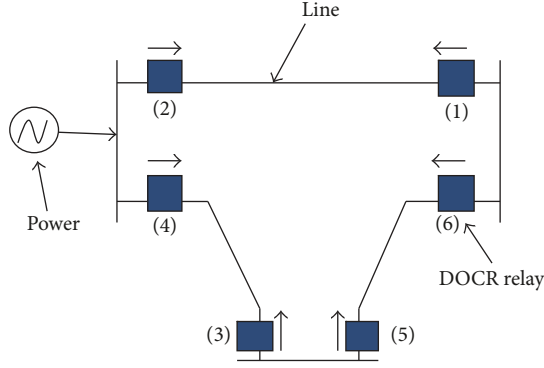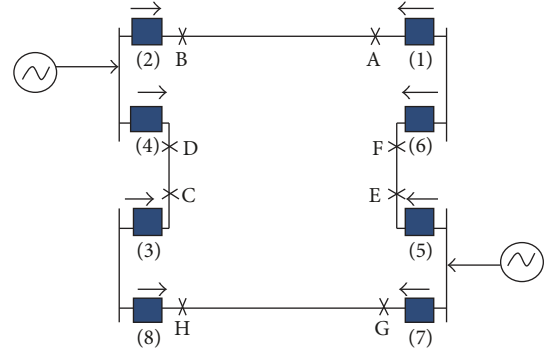
FIGURE 1: The 3-bus model.

FIGURE 2: The 4-bus model.

2.3. The Standard IEEE System of 3-Bus. There are six overcurrent relays in this model. According to the number of relays, the value assigned to each of N_{cl} and N_{far} is 6 and the number of decision variables is 12, and this means TDS_1 to TDS_6 and the variables PS_1 to PS_6. Figure 1 shows the 3-bus model.

Mathematically the objective function can be written as

$$\min F = \sum_{i=1}^{6} T^i_{\text{pri-cl-in}} + \sum_{i=1}^{6} T^j_{\text{pri-far-bus}}, \tag{10}$$

where

$$T^i_{\text{pri-cl-in}} = \frac{0.14 \times TDS^i}{\left(I^i_f / \left(PS^i \times CT^i_{\text{pri-rating}}\right)\right)^{0.02} - 1}, \tag{11}$$

$$T^j_{\text{pri-far-bus}} = \frac{0.14 \times TDS^j}{\left(I^j_f / \left(PS^j \times CT^j_{\text{pri-rating}}\right)\right)^{0.02} - 1}.$$

The values of constants I^i_f, $CT^i_{\text{pri-rating}}$, I^j_f, and $CT^j_{\text{pri-rating}}$ are shown in Table 6.

Constraints imposed on the 3-bus system are as follows.

Limits on Variables TDS_i. $TDS^{\min}_i \leq TDS_i \leq TDS^{\max}_i$, where i varies from 1 to 6.

Limits on Variables PS_i. $PS^{\min}_i \leq PS_i \leq PS^{\max}_i$, where i varies from 1 to 6.

Another constraint limits each term of objective between 0.05 and 1.

Selectivity constraints on working time of backup relay and the primary relay are given in the following relation:

$$T^{\text{backup}}_i - T^{\text{primary}}_i \geq CTI, \tag{12}$$

where CTI takes the value 0.3. Here,

$$T^{\text{backup}} = \frac{0.14 \times TDS^x}{\left(I^i_f / \left(PS^x \times CT^i_{\text{pri-rating}}\right)\right)^{0.02} - 1},$$

$$T^{\text{primary}} = \frac{0.14 \times TDS^y}{\left(I^i_f / \left(PS^y \times CT^j_{\text{pri-rating}}\right)\right)^{0.02} - 1}. \tag{13}$$
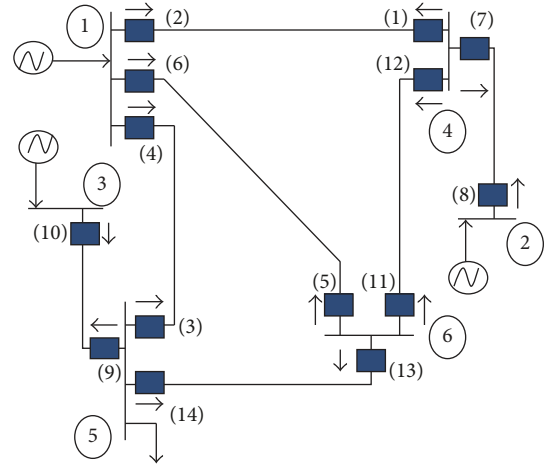

FIGURE 3: The 6-bus model.

The values of the constants for T_{backup} and T_{primary} of 3-bus model are given in Table 7.

2.4. The Standard IEEE System of 4-Bus. In the IEEE 4-bus model, there are 8 overcurrent relays. Accordingly, the value of N_{cl} and N_{far} is 8, which is twice the number of transmission lines and the number of decision variables is 16. The 4-bus model is shown in Figure 2. CTI takes the value for this model as 0.3. Total selectivity constraints are 9.

Moreover, the values of constants for the 4-bus model are given in Tables 8 and 9.

2.5. The Standard IEEE System of 6-Bus. In this section, the IEEE 6-bus model is elaborated. Here, value of N_{cl} and N_{far} is 14. Hence, there are 28 variables in this problem, namely, TDS_1 to TDS_{14} and PS_1 to PS_{14}. The 6-bus model is shown in Figure 3. CTI takes the value 0.2 for this model. There are 48 selectivity constraints in this problem. Based on the observation of [48], we have relaxed 10 constraints. The values of constants I^i_f, $CT^i_{\text{pri-rating}}$, I^j_f, and $CT^j_{\text{pri-rating}}$ for Model 3 are given in Tables 10 and 11. A summary of all components involved in models of IEEE 3-bus, 4-bus, and 6-bus is presented in Table 5.

INPUT: Set ecosize, create population of organisms X_i, $i = 1, 2, 3, \ldots$, ecosize, initialize X_i, Set stopping criteria,
Initialize SA parameters: Initial temperature T_{init}, Final temperature T_{fin}, Cooling rate δ.
OUTPUT: Optimal schedule
(1) Identify the best organism X_{best}
(2)   **While** stopping criterion is not met
(3)   **For** $i = 1$ to *ecosize*
(4)   **Mutualism Phase**
(5)   Simulated annealing on X_i
(6)   Simulated annealing on X_j
(7)   Transform X_i and X_j
(8)   **Commensalism Phase**
(9)   Simulated annealing on X_i
(10)   Apply Eq (15) to reduce the temperature
(11)   Transform X_i
(12)   **Parasitism Phase**
(13)   Create *parasite_vector*
(14)   Update X_j
(15)   Transform X_j
(16)   Identify the best organism X_{best}
(17)   **End For**
(18)   **End While**

ALGORITHM 1: The pseudo code for SASOS [47].

3. Hybridization of Simulated Annealing (SA) and Symbiotic Organism Search (SOS)

The hybrid algorithm is named as SASOS [47]. In SASOS algorithm, the new solutions are created using the three phases of SOS algorithm by shifting the earlier solutions towards randomly picked solutions from the system [49]. The convergence rate of SOS algorithm is slow due to its strategy for locating the global optima. If the updated solution is better than previous solution, the convergence will be faster. Therefore, to further improve the convergence rate, Simulated Annealing technique is employed in the mutualism and commensalism phase of the SOS algorithm. The parasitism stage is left unchanged [47]. A pseudo code for SASOS algorithm is given in Algorithm 1. The SA technique accepts poor neighbour solutions along with the current best solutions by implementing certain probability. In each generation, probability of selecting the bad solutions is higher at the initial stages but decreases at the later stages of the search. This probability of either selecting poor solutions or good ones is calculated as in

$$P_r = \exp\left(\frac{-(f(X_i^*) - f(X_i))}{T}\right), \qquad (14)$$

where $f(X_i^*)$ and $f(X_i)$ are the fitness values of ith solution and current best solutions, respectively, and here T is the control parameter. Equation (15) is used to reduce the temperature in Simulated Annealing:

$$T = \delta^i * T_0 + T_f. \qquad (15)$$

4. Experimental Settings and Discussion

4.1. Experimental Settings. The parameters involved in SASOS are ecosize, initial temperature T_{init}, final temperature T_{final}, and cooling rate δ. The ecosize is taken as 50 for all the cases. The value of initial temperature T_{init} is taken as 1, while the final temperature is 10^{-10} and cooling rate δ is taken as 1.

For a fair comparison, a total of 30 simulations were performed for each of the three cases and the current best solution through the simulation was recorded as the current best solution.

4.2. Discussion. Performance of the SASOS algorithm is analyzed based on the best objective values (see Figures 5, 7, and 9) and total function evaluations taken by algorithms (see Figures 4, 6, and 8). The outcomes of SASOS are highlighted and compared with the values obtained by different versions of Differential Evolution and other algorithms available in the literature [17]. The results for 3-bus, 4-bus, and 6-bus systems are given in Tables 1, 2, and 3, respectively.

The best solutions obtained by SASOS and other versions of DE for IEEE 3-bus model in terms of best decision features, minimum objective function value, and number of function evaluations taken to complete each simulation are given in Table 1 and Figures 4 and 5. Here, it is evident that, in terms of objective function value, DE gave the worse objective value as 4.8422 and all the other versions of DE algorithm gave almost similar values. On the other hand, SASOS gave us an objective value 4.7201 which is much better than other algorithms. However, if we compare the number of function evaluations (NFE), then the performances of DE and its variants are worse as compared to SASOS algorithm as it took only 31500 NFE to

TABLE 1: Optimal values of design variables, objective values, and function evaluations obtained by SASOS, DE, and modified DE: IEEE 3-bus system.

	TDS_1	TDS_2	TDS_3	TDS_4	TDS_5	TDS_6	PS_1	PS_2	PS_3	PS_4	PS_5	PS_6	F	NFE
DE	0.05	0.2194	0.05	0.2135	0.19498	0.1953	1.25	1.25	1.2500	1.4605	1.25	1.25	4.8422	78360
MDE-1	0.05	0.2178	0.05	0.2090	0.1812	0.1807	1.25	1.25	1.25	1.4999	1.5	1.4999	4.80707	72350
MDE-2	0.05	0.1979	0.05	0.2094	0.1847	0.1827	1.25	1.4999	1.25	1.4999	1.4318	1.4619	4.7873	73350
MDE-3	0.05	0.1988	0.05	0.2090	0.1812	0.1807	1.25	1.4849	1.25	1.4999	1.4998	1.4999	4.7822	97550
MDE-4	0.05	0.1976	0.05	0.2090	0.1812	0.1806	1.25	1.4999	1.25	1.4999	1.4999	1.4999	4.7806	69270
MDE-5	0.05	0.1976	0.05	0.2090	0.1812	0.1806	1.25	1.5	1.25	1.5	1.5	1.5	4.7806	38250
SASOS	0.05	0.207161	0.05	0.30155	0.203466	0.091295	1.44387	1.25	1.252555	1.265668	1.2500	1.359382	*4.7201*	*31500*

FIGURE 4: Comparison of number of function evaluations done, for obtaining the best results, by SASOS algorithm with DE and its modified versions for 3-bus model.
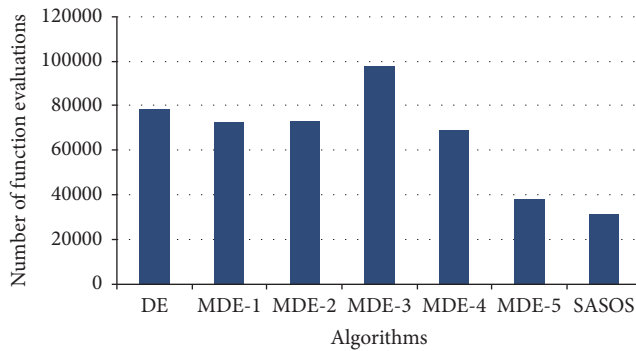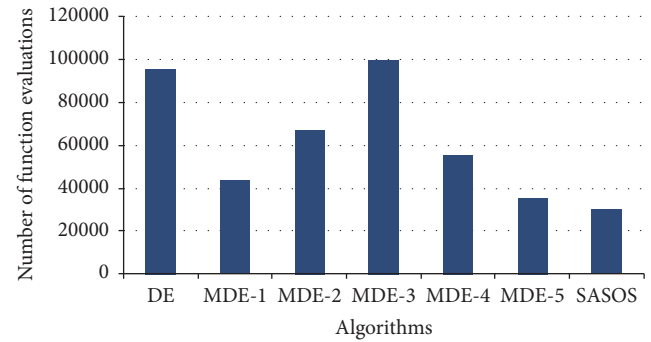

FIGURE 6: Comparison of number of function evaluations done, for obtaining the best results, by SASOS algorithm with DE and its modified versions for 4-bus model.
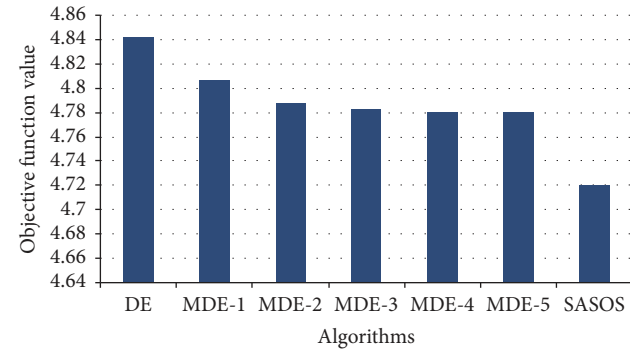

FIGURE 5: Comparison of best objective values obtained by SASOS algorithm with DE and its modified versions for 3-bus model.
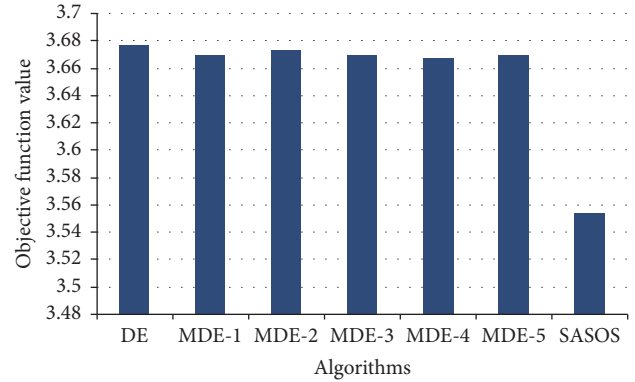
FIGURE 7: Comparison of best objective values obtained by SASOS algorithm with DE and its modified versions for 4-bus model.

complete the simulations. Thus, SASOS is significantly better than all the other algorithms under consideration.

The simulation results of IEEE 4-bus model are given in Table 2 and Figures 6 and 7, respectively. It is observed for the IEEE 4-bus model that DE algorithm and all the variants of DE algorithm performed in a similar manner in terms of objective function values with MDE-4 giving a slightly better value than other variant algorithms of DE. But SASOS outperformed the algorithms under consideration in terms of the number of function evaluations (NFE). The better performance was shown by SASOS, which took 30000 NFE to converge to a solution 3.5533.

Furthermore, the results for IEEE 6-bus model as in Table 3 and Figures 8 and 9, in terms of best objective function value, are again slightly different to each other with MDE-4 and MDE-5 giving slightly improved solutions than other variant algorithms of DE. On the other hand, SASOS gave us an objective value 9.8948 which is much better than other results in the table. However, in terms of NFE, the worst convergence rate was shown by DE while SASOS took 35000 NFE to get the best solution presented in the table.

Summarily, it can be observed from Tables 1, 2, and 3 that SASOS provides better solutions to the given problems compared to DE. Also, the number of function evaluations

Table 2: Optimal values of design variables, objective values, and function evaluations obtained by SASOS, DE, and modified DE: IEEE 4-bus system.

	TDS_1	TDS_2	TDS_3	TDS_4	TDS_5	TDS_6	TDS_7	TDS_8	PS_1	PS_2	PS_3	PS_4	PS_5	PS_6	PS_7	PS_8	F	NFE
DE	0.05	0.2248	0.05	0.1515	0.1264	0.05	0.1337	0.0500	1.2734	1.25	1.2500	1.4997	1.4997	1.25	1.5	1.25	3.6774	95400
MDE-1	0.05	0.2121	0.0500	0.1515	0.1264	0.05	0.1338	0.05	1.2733	1.4998	1.2500	1.4996	1.5	1.2500	1.4997	1.2500	3.6694	43400
MDE-2	0.05	0.2123	0.05	0.1515	0.1264	0.05	0.1371	0.05	1.2733	1.4959	1.2500	1.4997	1.5	1.25	1.4274	1.25	3.6734	67200
MDE-3	0.05	0.2121	0.05	0.1515	0.1264	0.05	0.1338	0.05	1.2733	1.5	1.25	1.4995	1.4997	1.25	1.4995	1.25	3.6692	99700
MDE-4	0.05	0.2121	0.05	0.1515	0.1262	0.05	0.1337	0.05	1.25	1.5	1.25	1.5	1.5	1.25	1.4998	1.25	3.6674	55100
MDE-5	0.05	0.2121	0.05	0.1515	0.1264	0.0500	0.1337	0.0500	1.2734	1.4999	1.2500	1.4999	1.5	1.2500	1.5	1.25	3.6694	35330
SASOS	0.0500	0.2183	0.0500	0.1430	0.1265	0.0500	0.1411	0.0500	1.2800	1.2500	1.2500	1.2517	1.2500	1.2500	1.2513	1.2500	3.5533	30000

TABLE 3: Optimal values of design variables, objective values, and function evaluations obtained by SASOS, DE, and modified DE: IEEE 6-bus system.

	DE	MDE-1	MDE-2	MDE-3	MDE-4	MDE-5	SASOS
TDS_1	0.1173	0.1171	0.1149	0.1034	0.1144	0.1024	0.1425
TDS_2	0.2082	0.1866	0.2037	0.1863	0.1864	0.1863	0.2076
TDS_3	0.0997	0.0965	0.0982	0.0961	0.0947	0.0946	0.0622
TDS_4	0.1125	0.1119	0.10367	0.1125	0.1006	0.1067	0.1010
TDS_5	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0524
TDS_6	0.0580	0.0500	0.0500	0.0500	0.0500	0.0500	0.0536
TDS_7	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0501
TDS_8	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0501
TDS_9	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0539
TDS_{10}	0.0719	0.0706	0.0575	0.0703	0.0701	0.0563	0.0506
TDS_{11}	0.0649	0.0649	0.0667	0.0649	0.0649	0.0650	0.0500
TDS_{12}	0.0617	0.0617	0.0566	0.0509	0.0509	0.0553	0.0502
TDS_{13}	0.0500	0.0500	0.0635	0.0500	0.0500	0.0500	0.0500
TDS_{14}	0.0856	0.0860	0.0859	0.0857	0.0709	0.0709	0.0824
PS_1	1.2505	1.2515	1.2635	1.4995	1.2602	1.4991	1.4593
PS_2	1.2500	1.4959	1.2993	1.4999	1.4987	1.4999	1.2545
PS_3	1.2512	1.2525	1.2622	1.2575	1.2761	1.2771	1.2500
PS_4	1.2515	1.2632	1.4322	1.2508	1.4992	1.3650	1.3348
PS_5	1.2500	1.2500	1.2500	1.2500	1.2500	1.2500	1.2511
PS_6	1.2500	1.3822	1.3885	1.3810	1.3814	1.3818	1.2734
PS_7	1.2500	1.2500	1.2508	1.2500	1.2500	1.2500	1.2502
PS_8	1.2500	1.2501	1.2500	1.2500	1.2505	1.2500	1.2737
PS_9	1.2502	1.2500	1.2514	1.2500	1.2500	1.2500	1.2508
PS_{10}	1.2502	1.2501	1.4970	1.2521	1.2500	1.4996	1.2536
PS_{11}	1.4998	1.4999	1.4759	1.4998	1.4999	1.4998	1.5000
PS_{12}	1.2575	1.2529	1.4700	1.4997	1.5000	1.3931	1.2501
PS_{13}	1.4805	1.4664	1.2728	1.4647	1.4615	1.4613	1.4190
PS_{14}	1.2557	1.2500	1.2624	1.2540	1.4979	1.4974	1.2515
F	10.6272	10.5067	10.6238	10.4370	10.3812	10.3514	*9.8948*
NFE	212190	72960	18180	101580	100860	106200	*35000*
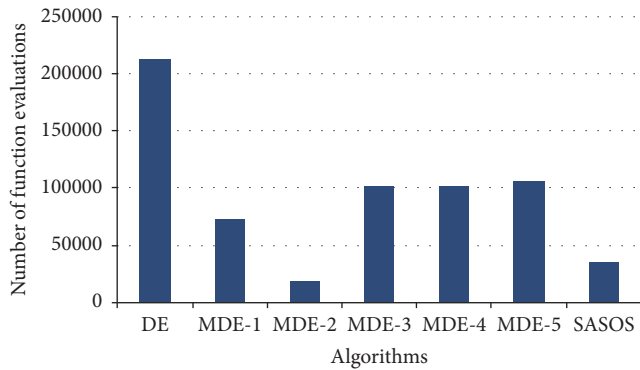
FIGURE 8: Comparison of number of function evaluations done, for obtaining the best results, by SASOS algorithm with DE and its modified versions for 6-bus model.

FIGURE 9: Comparison of best objective values obtained by SASOS algorithm with DE and its modified versions for 6-bus model.

(NFE) taken by SASOS algorithm is considerably reduced in comparison to DE algorithms. In Table 4, the objective function values obtained by SASOS are compared with the values obtained by other algorithms such as DE, RST2, SOMA, and SOMGA for all the three models, as reported in [50], LX-POL and LX-PM [51], and MDE algorithms [17]. It can be observed from Table 4 that SASOS provided better

TABLE 4: Comparison of results obtained by SASOS and other algorithms for IEEE 3-, 4-, and 6-bus systems.

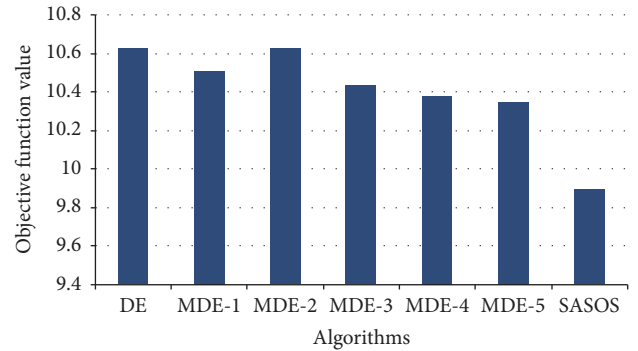| Algorithm	3-bus model	4-bus model	6-bus model
SASOS	4.7201	3.5533	9.8948
DE	4.8421	3.6774	10.6272
MDE-1	4.8069	3.6694	10.5067
MDE-2	4.7872	3.6734	10.6238
MDE-3	4.7822	3.6692	10.4370
MDE-4	4.7806	3.6674	10.3812
MDE-5	4.7806	3.6694	10.3514
RST-2	4.8354	3.7050	10.6192
GA	5.0761	3.8587	13.7996
SOMA	8.0101	3.7892	26.1495
SOMGA	4.7898	3.6745	10.3578
LX-POL	4.8265	3.5749	10.6028
LX-PM	4.8286	3.5830	10.6219

TABLE 5: The summary table of different components involved in the problem of DOCR.

Number	IEEE 3-bus	IEEE 4-bus	IEEE 6-bus
Number of lines	3	4	7
Number of DOCRs (relays)	6	8	14
Number of decision variables	12	16	28
Number of selectivity constraints	8	9	38
Number of restricted constraints	24	32	104

TABLE 6: Values of constants for objective function of 3-bus model.

	$T^i_{\text{pri-cl-in}}$			$T^i_{\text{pri-far-bus}}$	
TDS^i	I^i_f	$\text{CT}^i_{\text{pri-rating}}$	TDS^j	I^j_f	$\text{CT}^j_{\text{pri-rating}}$
TDS^1	9.46	2.06	TDS^2	100.63	2.06
TDS^2	26.91	2.06	TDS^1	14.08	2.06
TDS^3	8.81	2.23	TDS^4	136.23	2.23
TDS^4	37.68	2.23	TDS^3	12.07	2.23
TDS^5	17.93	0.8	TDS^6	19.2	0.8
TDS^6	14.35	0.8	TDS^5	25.9	0.8

TABLE 7: Values of constants for T_{backup} and T_{primary} of 3-bus model.

	T^i_{backup}			T^i_{primary}	
x	I^i_f	$\text{CT}^i_{\text{pri-rating}}$	y	I^j_f	$\text{CT}^j_{\text{pri-rating}}$
5	14.08	0.8	1	14.08	2.06
6	12.07	0.8	3	12.07	2.23
4	25.9	2.23	5	25.9	0.8
2	14.35	0.8	6	14.35	2.06
5	9.46	0.8	1	9.46	2.06
6	8.81	0.8	3	8.81	2.23
2	19.2	2.06	6	19.2	0.8
4	17.93	2.23	5	17.93	0.8

results for all the three systems among all results quoted in [17], in terms of best objective values.

5. Conclusion

We present a conclusion of this research as follows:

(i) The problems of optimal coordination of directional overcurrent relays are highly nonlinear, NP-hard, and highly constrained in nature.

(ii) Dealing with the DOCR problems, use of efficient metaheuristic is needed.

(iii) SASOS is implemented to solve the problem of DOCRs for standard IEEE 3-, 4-, and 6-bus systems.

TABLE 8: Values of constants for objective function of 4-bus model.

	$T^i_{\text{pri-cl-in}}$			$T^i_{\text{pri-far-bus}}$	
TDS^i	I^i_f	$\text{CT}^i_{\text{pri-rating}}$	TDS^j	I^j_f	$\text{CT}^j_{\text{pri-rating}}$
TDS^1	20.32	0.48	TDS^2	23.75	0.48
TDS^2	88.85	0.48	TDS^1	12.48	0.48
TDS^3	13.61	1.1789	TDS^4	31.92	1.1789
TDS^4	116.81	1.1789	TDS^3	10.38	1.1789
TDS^5	116.7	1.5259	TDS^6	12.07	1.5259
TDS^6	16.67	1.5259	TDS^5	31.92	1.5259
TDS^7	71.7	1.2018	TDS^8	11	1.2018
TDS^8	19.27	1.2018	TDS^7	18.91	1.2018

TABLE 9: Values of constants for T_{backup} and T_{primary} of 4-bus model.

	T_{backup}^i			T_{primary}^i	
x	I_f^i	$CT_{\text{pri-rating}}^i$	y	I_f^j	$CT_{\text{pri-rating}}^j$
5	20.32	1.5259	1	20.32	0.48
5	12.48	1.5259	1	12.48	0.48
7	13.61	1.2018	3	13.61	1.1789
7	10.38	1.2018	3	10.38	1.1789
1	1.16	0.48	4	116.81	1.1789
2	12.07	0.48	6	12.07	1.1789
2	16.67	0.48	6	16.67	1.5259
4	11	1.1789	8	11	1.2018
4	19.27	1.1789	8	19.27	1.2018

TABLE 10: Values of constants for objective function of 6-bus model.

	$T_{\text{pri-cl-in}}^i$			$T_{\text{pri-far-bus}}^i$	
TDS^i	I_f^i	$CT_{\text{pri-rating}}^i$	TDS^j	I_f^j	$CT_{\text{pri-rating}}^j$
TDS^1	2.5311	0.2585	TDS^2	5.9495	0.2585
TDS^2	2.7376	0.2585	TDS^1	5.3752	0.2585
TDS^3	2.9723	0.4863	TDS^4	6.6641	0.4863
TDS^4	4.1477	0.4863	TDS^3	4.5897	0.4863
TDS^5	1.9545	0.7138	TDS^6	6.2345	0.7138
TDS^6	2.7678	0.7138	TDS^5	4.2573	0.7138
TDS^7	3.8423	1.746	TDS^8	6.3694	1.746
TDS^8	5.618	1.746	TDS^7	4.1783	1.746
TDS^9	4.6538	1.0424	TDS^{10}	3.87	1.0424
TDS^{10}	3.5261	1.0424	TDS^9	5.2696	1.0424
TDS^{11}	2.584	0.7729	TDS^{12}	6.1144	0.7729
TDS^{12}	3.8006	0.7729	TDS^{11}	3.9005	0.7729
TDS^{13}	2.4143	0.5879	TDS^{14}	2.9011	0.5879
TDS^{14}	5.3541	0.5879	TDS^{13}	4.335	0.5879

TABLE 11: Values of constants for T_{backup} and T_{primary} of 6-bus model.

	T_{backup}^i			T_{primary}^i	
x	I_f^i	$CT_{\text{pri-rating}}^i$	y	I_f^j	$CT_{\text{pri-rating}}^j$
8	4.0909	1.746	1	5.3752	0.2585
11	1.2886	0.7729	1	5.3752	0.2585
8	2.9323	1.746	1	2.5311	0.2585
3	0.6213	0.4863	2	2.7376	0.2585
3	1.6658	0.4863	2	5.9495	0.2585
10	0.0923	1.0424	3	4.5897	0.4863
10	2.561	1.0424	3	2.9723	0.4863
13	1.4995	0.5879	3	4.5897	0.4863
1	0.8869	0.2585	4	4.1477	0.4863
1	1.5243	0.2585	4	6.6641	0.4863
12	2.5444	0.7729	5	4.2573	0.7138
12	1.4549	0.7729	5	1.9545	0.7138
14	1.7142	0.5879	5	4.2573	0.7138
3	1.4658	0.4863	6	6.2345	0.7138
3	1.1231	0.2585	6	6.2345	0.7138
11	2.1436	0.7729	7	4.1783	1.746
2	2.0355	0.2585	7	4.1783	1.746
11	1.9712	0.7729	7	3.8423	1.746
2	1.8718	0.2585	7	3.8423	1.746
13	1.8321	0.5879	9	5.2696	1.0424
4	3.4386	0.4863	9	5.2696	1.0424
13	1.618	0.5879	9	4.6538	1.0424
4	3.0368	0.4863	9	4.6538	1.0424
14	2.0871	0.5879	11	3.9005	0.7729
6	1.8138	0.7138	11	3.9005	0.7729
14	1.4744	0.5879	11	2.584	0.7729
6	1.1099	0.7138	11	2.584	0.7729
8	3.3286	1.746	12	3.8006	0.7729
2	0.4734	0.2585	12	3.8006	0.7729
8	4.5736	1.746	12	6.1144	0.7729
2	1.5432	0.2585	12	6.1144	0.7729
12	2.7269	0.7729	13	4.335	0.5879
6	1.6085	0.7138	13	4.335	0.5879
12	1.836	0.7729	13	2.4143	0.5879
10	2.026	1.0424	14	2.9011	0.5879
4	0.8757	0.4863	14	2.9011	0.5879
10	2.7784	1.0424	14	5.3541	0.5879
4	2.5823	0.4863	14	5.3541	0.5879

(iv) The outcome of our simulations shows that SASOS can efficiently minimize all the three models of the problem.

(v) The efficiency of SASOS can be observed from the minimum function evaluations required by the algorithm to reach the optimum as compared to other standard algorithms.

(vi) In future, one can extend this work to solve problems of higher buses and complex power systems. Moreover, extensive statistical analysis and parameters tuning can further highlight and improve the efficiency of SASOS.

Nomenclature

α, β, γ:	Constants according to IEEE standard
δ:	Cooling rate in Simulated Annealing
CT:	Current transformer
$CT_{\text{pri-rating}}$:	Primary rating of current transformer
CTI:	Coordination time interval
DE:	Differential Evolution
DOCR:	Directional overcurrent relays
F:	Objective function
$f(X_i)$:	Fitness value at the ith solution
$f(X_i^*)$:	Current best solution
I_f:	Fault current at the current transformer initial terminal
I_{relay}:	The current, seen by relay
MDE:	Modified Differential Evolution
N_{cl}:	Number of relays responding for close end fault
N_{far}:	Number of relays responding for far-bus fault

PS: Plug settings
SA: Simulated Annealing
SOS: Symbiotic Organism Search
T: Operating time of relay
T_{backup}: Operating time of backup relay
T_{final}: Final temperature
T_{init}: Initial temperature
$T_{\text{pri-cl-in}}$: The relay operation time to clear near end fault
$T_{\text{pri-far-bus}}$: The relay operation time in case of far end fault
T_{primary}: Operating time of primary relay
TDS: Time dial settings
NFE: Net function evaluations.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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