Hindawi
Complexity
Volume 2018, Article ID 4605769, 11 pages
https://doi.org/10.1155/2018/4605769

Research Article

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

Muhammad Sulaiman, Ashfaq Ahmad, Asfandyar Khan, and Shakoor Muhammad

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

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

Received 3 September 2017; Revised 5 December 2017; Accepted 21 December 2017; Published 23 January 2018

Academic Editor: Danilo Comminiello

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

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

where I_f denotes the fault current at the current transformer (CT) initial terminal and $\mathrm{CT}_{\text{pri-rating}}$ 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 $\mathrm{CT}_{\text{pri-rating}}$, which is a nonlinear equation:

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

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:

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

where

$$T^{i}_{\text{pri-cl-in}} = \frac{0.14 \times \mathrm{TDS}^{i}}{\left(I^{i}_{f} / \left(\mathrm{PS}^{i} \times \mathrm{CT}^{i}_{\text{pri-rating}}\right)\right)^{0.02} - 1},$$
$$T^{j}_{\text{pri-far-bus}} = \frac{0.14 \times \mathrm{TDS}^{j}}{\left(I^{j}_{f} / \left(\mathrm{PS}^{j} \times \mathrm{CT}^{j}_{\text{pri-rating}}\right)\right)^{0.02} - 1}, \tag{4}$$

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:

$$\mathrm{TDS}^{\min}_{i} \le \mathrm{TDS}_{i} \le \mathrm{TDS}^{\max}_{i}. \tag{5}$$

$\mathrm{TDS}^{\min}_{i}$ and $\mathrm{TDS}^{\max}_{i}$ 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:

$$\mathrm{PS}^{\min}_{i} \le \mathrm{PS}_{i} \le \mathrm{PS}^{\max}_{i}. \tag{6}$$

$\mathrm{PS}^{\min}_{i}$ and $\mathrm{PS}^{\max}_{i}$ 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

$$T^{\min}_{i} \le T_{i} \le T^{\max}_{i}. \tag{7}$$

$T^{\min}_{i}$ and $T^{\max}_{i}$ 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

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

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:

$$T^{\text{backup}}_{i} = \frac{0.14 \times \mathrm{TDS}^{x}}{\left(I^{i}_{f} / \left(\mathrm{PS}^{x} \times \mathrm{CT}^{i}_{\text{pri-rating}}\right)\right)^{0.02} - 1},$$
$$T^{\text{primary}}_{i} = \frac{0.14 \times \mathrm{TDS}^{y}}{\left(I^{i}_{f} / \left(\mathrm{PS}^{y} \times \mathrm{CT}^{i}_{\text{pri-rating}}\right)\right)^{0.02} - 1}. \tag{9}$$

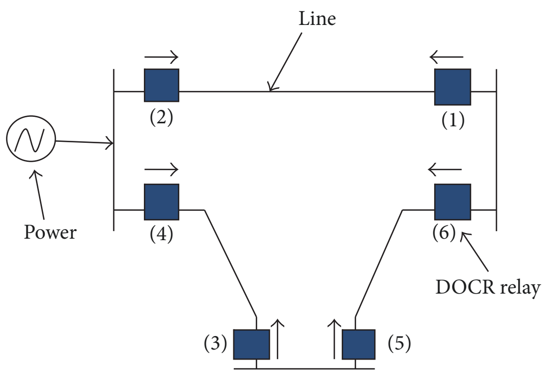

FIGURE 1: The 3-bus model.

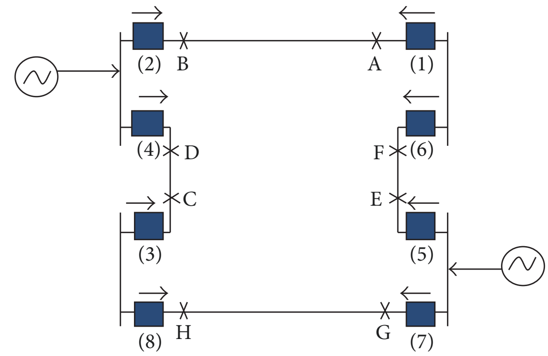

FIGURE 2: The 4-bus model.

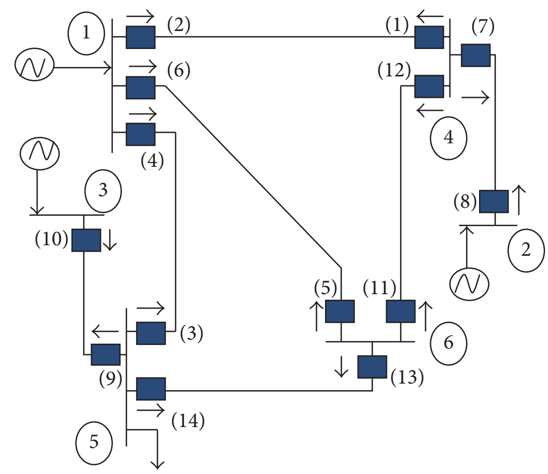

FIGURE 3: The 6-bus model.

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

$$T^{i}_{\text{pri-cl-in}} = \frac{0.14 \times \text{TDS}^{i}}{\left(I^{i}_{f} / \left(\text{PS}^{i} \times \text{CT}^{i}_{\text{pri-rating}}\right)\right)^{0.02} - 1},$$
$$T^{j}_{\text{pri-far-bus}} = \frac{0.14 \times \text{TDS}^{j}}{\left(I^{j}_{f} / \left(\text{PS}^{j} \times \text{CT}^{j}_{\text{pri-rating}}\right)\right)^{0.02} - 1}. \tag{11}$$

The values of constants I^{i}_{f}, $\text{CT}^{i}_{\text{pri-rating}}$, I^{j}_{f}, and $\text{CT}^{j}_{\text{pri-rating}}$ are shown in Table 6.

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

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

Limits on Variables PS_i. $\text{PS}_i^{\min} \le \text{PS}_i \le \text{PS}_i^{\max}$, 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:

$$T_i^{\text{backup}} - T_i^{\text{primary}} \ge \text{CTI}, \tag{12}$$

where CTI takes the value 0.3. Here,

$$T^{\text{backup}} = \frac{0.14 \times \text{TDS}^{x}}{\left(I^{i}_{f} / \left(\text{PS}^{x} \times \text{CT}^{i}_{\text{pri-rating}}\right)\right)^{0.02} - 1},$$
$$T^{\text{primary}} = \frac{0.14 \times \text{TDS}^{y}}{\left(I^{i}_{f} / \left(\text{PS}^{y} \times \text{CT}^{j}_{\text{pri-rating}}\right)\right)^{0.02} - 1}. \tag{13}$$

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}, $\text{CT}^{i}_{\text{pri-rating}}$, I^{j}_{f}, and $\text{CT}^{j}_{\text{pri-rating}}$ 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

Identify the best organism X_{best}
While stopping criterion is not met
  For $i = 1$ to *ecosize*
    Mutualism Phase
      Simulated annealing on X_i
      Simulated annealing on X_j
      Transform X_i and X_j
    Commensalism Phase
      Simulated annealing on X_i
        Apply Eq (15) to reduce the temperature
        Transform X_i
        Parasitism Phase
        Create *parasite_vector*
        Update X_j
        Transform X_j
    Identify the best organism X_{best}
  End For
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

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

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:

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

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*

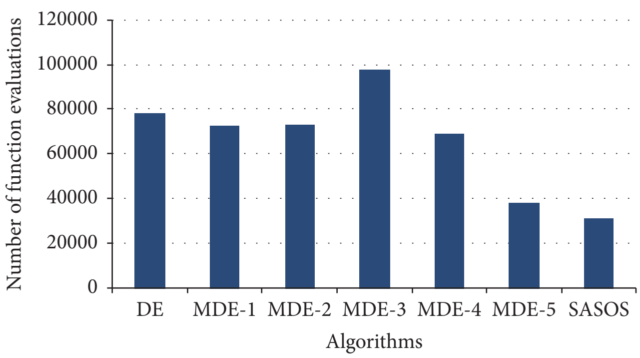

Figure 4: Comparison of number of function evaluations done, for obtaining the best results, by SASOS algorithm with DE and its modified versions for 3-bus model.

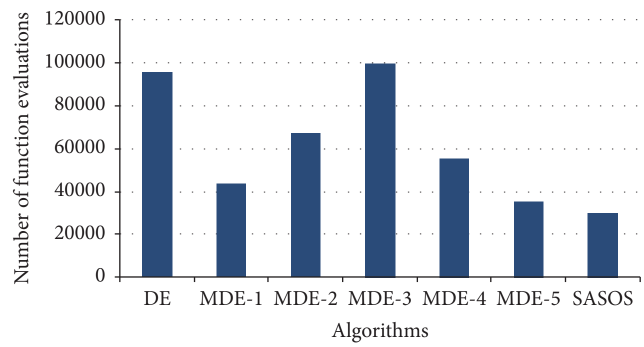

Figure 6: Comparison of number of function evaluations done, for obtaining the best results, by SASOS algorithm with DE and its modified versions for 4-bus model.

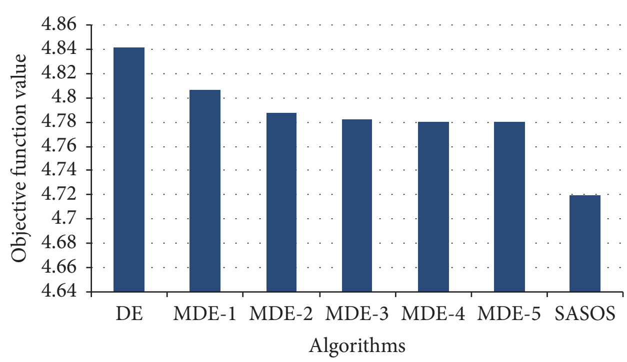

Figure 5: Comparison of best objective values obtained by SASOS algorithm with DE and its modified versions for 3-bus model.

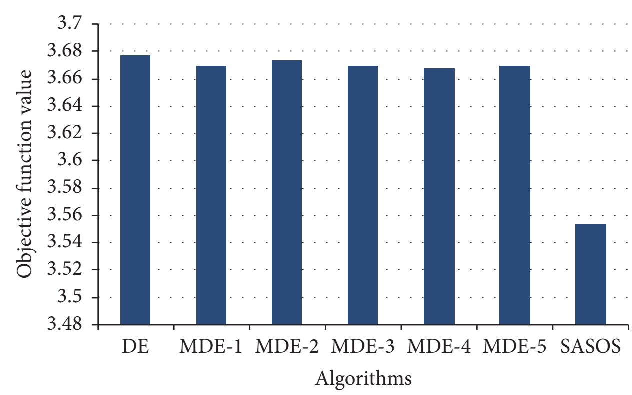

Figure 7: Comparison of best objective values obtained by SASOS algorithm with DE and its modified versions for 4-bus model.

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*

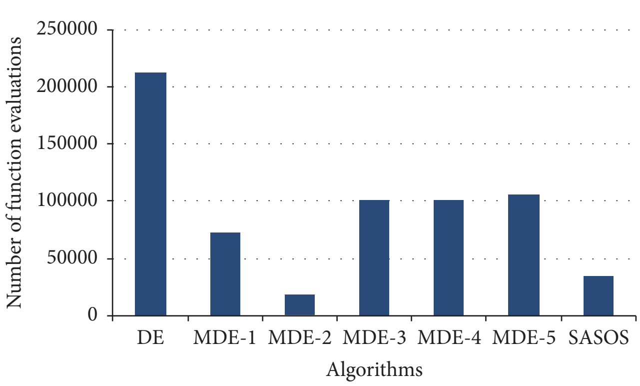

Figure 8: Comparison of number of function evaluations done, for obtaining the best results, by SASOS algorithm with DE and its modified versions for 6-bus model.

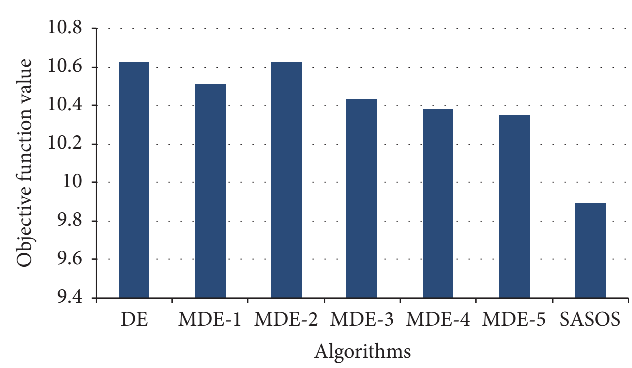

Figure 9: Comparison of best objective values obtained by SASOS algorithm with DE and its modified versions for 6-bus model.

(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	$CT^i_{\text{pri-rating}}$	TDS^j	I^j_f	$CT^j_{\text{pri-rating}}$
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

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

	T^i_{backup}			T^i_{primary}	
x	I^i_f	$CT^i_{\text{pri-rating}}$	y	I^j_f	$CT^j_{\text{pri-rating}}$
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

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	$CT^i_{\text{pri-rating}}$	TDS^j	I^j_f	$CT^j_{\text{pri-rating}}$
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^i_{backup}			$T^i_{primary}$	
x	I^i_f	$CT^i_{pri\text{-}rating}$	y	I^j_f	$CT^j_{pri\text{-}rating}$
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.

	$T^i_{pri\text{-}cl\text{-}in}$			$T^i_{pri\text{-}far\text{-}bus}$	
TDS^i	I^i_f	$CT^i_{pri\text{-}rating}$	TDS^j	I^j_f	$CT^j_{pri\text{-}rating}$
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

(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.

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

	T^i_{backup}			$T^i_{primary}$	
x	I^i_f	$CT^i_{pri\text{-}rating}$	y	I^j_f	$CT^j_{pri\text{-}rating}$
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

Nomenclature

- α, β, γ: Constants according to IEEE standard
- δ: Cooling rate in Simulated Annealing
- CT: Current transformer
- $CT_{pri\text{-}rating}$: 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.

References

[1] S. M. Abd-Elazim and E. S. Ali, "Load frequency controller design via BAT algorithm for nonlinear interconnected power system," *International Journal of Electrical Power & Energy Systems*, vol. 77, pp. 166–177, 2016.

[2] C. Zhang, Y. Wei, P. Cao, and M. Lin, "Energy storage system: current studies on batteries and power condition system," *Renewable & Sustainable Energy Reviews*, vol. 82, pp. 3091–3106, 2018.

[3] T. Ikegami, C. T. Urabe, T. Saitou, and K. Ogimoto, "Numerical definitions of wind power output fluctuations for power system operations," *Journal of Renewable Energy*, vol. 115, pp. 6–15, 2018.

[4] L. Van Dai, D. Duc, T. Le, and L. C. Quyen, "Improving power system stability with Gramian matrix-based optimal setting of a single series FACTS device: feasibility study in Vietnamese power system," *Complexity*, Art. ID 3014510, 21 pages, 2017.

[5] J. L. Calvo, S. H. Tindemans, and G. Strbac, "Incorporating failures of System protection schemes into power system operation," *Sustainable Energy, Grids and Networks*, vol. 8, pp. 98–110, 2016.

[6] B. Zou, M. Yang, J. Guo et al., "Insider threats of physical protection systems in nuclear power plants: prevention and evaluation," *Progress in Nuclear Energy*, 2017.

[7] L. Hewitson, M. Brown, and R. Balakrishnan, *Practical Power System Protection*, Elsevier, 2004.

[8] R. Thangaraj, M. Pant, and A. Abraham, "New mutation schemes for differential evolution algorithms and their application to the optimization of directional over-current relay settings," *Applied Mathematics and Computation*, vol. 216, no. 2, pp. 532–544, 2010.

[9] A. Ukil, B. Deck, and V. H. Shah, "Current-only directional overcurrent relay," *IEEE Sensors Journal*, vol. 11, no. 6, pp. 1403-1404, 2011.

[10] A. Sleva, *Protective Relay Principles*, CRC Press, 2009.

[11] W. Hwu, M. Hidayetogglu, W. C. Chew et al., "Thoughts on massively-parallel heterogeneous computing for solving large problems," in *Proceedings of Computing and Electromagnetics International Workshop (CEM)*, pp. 67-68, IEEE, Barcelona, Spain, June 2017.

[12] A. James Momoh, *Electric power system applications of optimization*, CRC Press, 2008.

[13] M. Sulaiman, A. Salhi, B. I. Selamoglu, and O. B. Kirikchi, "A plant propagation algorithm for constrained engineering optimisation problems," *Mathematical Problems in Engineering*, vol. 2014, Article ID 627416, 10 pages, 2014.

[14] M. Sulaiman and A. Salhi, "A seed-based plant propagation algorithm: the feeding station model," *The Scientific World Journal*, vol. 2015, Article ID 904364, 16 pages, 2015.

[15] J. A. Sueiro, E. Diaz-Dorado, E. Míguez, and J. Cidrás, "Coordination of directional overcurrent relay using evolutionary algorithm and linear programming," *International Journal of Electrical Power & Energy Systems*, vol. 42, no. 1, pp. 299–305, 2012.

[16] R. Thangaraj, T. R. Chelliah, and M. Pant, "Overcurrent relay coordination by differential evolution algorithm," in *Proceedings of the International Conference on Power Electronics, Drives and Energy Systems, PEDES 2012*, IEEE, Bengaluru, India, December 2012.

[17] R. Thangaraj, M. Pant, and K. Deep, "Optimal coordination of over-current relays using modified differential evolution algorithms," *Engineering Applications of Artificial Intelligence*, vol. 23, no. 5, pp. 820–829, 2010.

[18] M. Mohseni, A. Afroomand, and F. Mohsenipour, "Optimum coordination of overcurrent relays using SADE algorithm," in *Proceedings of the 16th Electrical Power Distribution Conference, EPDC*, April 2011.

[19] M. R. Asadi and S. M. Kouhsari, "Optimal overcurrent relays coordination using particle-swarm-optimization algorithm," in *Proceedings of Power Systems Conference and Exposition, PSCE*, IEEE, Seattle, WA, USA, March 2009.

[20] H. H. Zeineldin, E. F. El-Saadany, and M. M. A. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Electric Power Systems Research*, vol. 76, no. 11, pp. 988–995, 2006.

[21] M. M. Mansour, S. F. Mekhamer, and N. E.-S. El-Kharbawe, "A modified particle swarm optimizer for the coordination of directional overcurrent relays," *IEEE Transactions on Power Delivery*, vol. 22, no. 3, pp. 1400–1410, 2007.

[22] H. Leite, J. Barros, and V. Miranda, "The evolutionary algorithm EPSO to coordinate directional overcurrent relays," in *Proceedings of the 10th IET International Conference on Developments in Power System Protection, DPSP 2010*, IET, UK, April 2010.

[23] A. Fetanat, G. Shafipour, and F. Ghanatir, "Box-Muller harmony search algorithm for optimal coordination of directional overcurrent relays in power system," *Scientific Research and Essays*, vol. 6, no. 19, pp. 4079–4090, 2011.

[24] J. Moirangthem, S. S. Dash, and R. Ramaswami, "Zero-one integer programming approach to determine the minimum break point set in multi-loop and parallel networks," *Journal of Electrical Engineering & Technology*, vol. 7, no. 2, pp. 151–156, 2012.

[25] F. Xue, Y. Xu, H. Zhu, S. Lu, T. Huang, and J. Zhang, "Structural evaluation for distribution networks with distributed generation based on complex network," *Complexity*, vol. 2017, Article ID 7539089, 10 pages, 2017.

[26] M. Singh, B. K. Panigrahi, and R. Mukherjee, "Optimum coordination of overcurrent relays using CMA-ES algorithm," in *Proceedings of International Conference on Power Electronics, Drives and Energy Systems, PEDES 2012*, IEEE, Bengaluru, India, December 2012.

[27] T. Amraee, "Coordination of directional overcurrent relays using seeker algorithm," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1415–1422, 2012.

[28] T. R. Chelliah, R. Thangaraj, S. Allamsetty, and M. Pant, "Coordination of directional overcurrent relays using opposition based chaotic differential evolution algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 55, pp. 341–350, 2014.

[29] J. Moirangthem, Krishnanand K.R., S. S. Dash, and R. Ramaswami, "Adaptive differential evolution algorithm for solving non-linear coordination problem of directional overcurrent relays," *IET Generation, Transmission & Distribution*, vol. 7, no. 4, pp. 329–336, 2013.

[30] M. Singh, B. K. Panigrahi, and A. R. Abhyankar, "Optimal coordination of electro-mechanical-based overcurrent relays using artificial bee colony algorithm," *International Journal of Bio-Inspired Computation*, vol. 5, no. 5, pp. 267–280, 2013.

[31] R. Benabid, M. Zellagui, A. Chaghi, and M. Boudour, "Application of firefly algorithm for optimal directional overcurrent relays coordination in the presence of IFCL," *International Journal of Intelligent Systems and Applications*, vol. 6, no. 2, pp. 44–53, 2014.

[32] M. H. Hussain, I. Musirin, A. F. Abidin, and S. R. A. Rahim, "Modified swarm firefly algorithm method for directional overcurrent relay coordination problem," *Journal of Theoretical and Applied Information Technology*, vol. 66, no. 3, pp. 741–755, 2014.

[33] M. Zellagui, R. Benabid, M. Boudour, and A. Chaghi, "Optimal overcurrent relays coordination in the presence multi tcsc on power systems using BBO algorithm," *International Journal of Intelligent Systems and Applications*, vol. 7, no. 2, pp. 13–20, 2015.

[34] I. A. Mohamed and M. Kowsalya, "Optimal size and siting of multiple distributed generators in distribution system using bacterial foraging optimization," *Swarm and Evolutionary Computation*, vol. 15, pp. 58–65, 2014.

[35] S. Devi and M. Geethanjali, "Application of modified bacterial foraging optimization algorithm for optimal placement and sizing of distributed generation," *Expert Systems with Applications*, vol. 41, no. 6, pp. 2772–2781, 2014.

[36] P. K. Ray and B. Subudhi, "Neuro-evolutionary approaches to power system harmonics estimation," *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 212–220, 2015.

[37] S. Naveen, K. S. Kumar, and K. Rajalakshmi, "Distribution system reconfiguration for loss minimization using modified bacterial foraging optimization algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 69, pp. 90–97, 2015.

[38] K. S. Kumar and T. Jayabarathi, "A novel power system reconfiguration for a distribution system with minimum load balancing index using bacterial foraging optimization algorithm," *Frontiers in Energy*, vol. 6, no. 3, pp. 260–265, 2012.

[39] E. S. Ali, "Optimization of power system stabilizers using BAT search algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 61, pp. 683–690, 2014.

[40] I. A. Farhat and M. E. El-Hawary, "Dynamic adaptive bacterial foraging algorithm for optimum economic dispatch with valve-point effects and wind power," *IET Generation, Transmission & Distribution*, vol. 4, no. 9, pp. 989–999, 2010.

[41] W. Al-Saedi, S. W. Lachowicz, D. Habibi, and O. Bass, "Power flow control in grid-connected microgrid operation using particle swarm optimization under variable load conditions," *International Journal of Electrical Power & Energy Systems*, vol. 49, no. 1, pp. 76–85, 2013.

[42] R. P. Singh, V. Mukherjee, and S. P. Ghoshal, "Particle swarm optimization with an aging leader and challengers algorithm for optimal power flow problem with FACTS devices," *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 1185–1196, 2015.

[43] M. Basu, "Modified particle swarm optimization for nonconvex economic dispatch problems," *International Journal of Electrical Power & Energy Systems*, vol. 69, pp. 304–312, 2015.

[44] A. Ameli, S. Bahrami, F. Khazaeli, and M.-R. Haghifam, "A multiobjective particle swarm optimization for sizing and placement of DGs from DG owner's and distribution company's viewpoints," *IEEE Transactions on Power Delivery*, vol. 29, no. 4, pp. 1831–1840, 2014.

[45] S. Devi and M. Geethanjali, "Optimal location and sizing of distribution static synchronous series compensator using particle swarm optimization," *International Journal of Electrical Power & Energy Systems*, vol. 62, pp. 646–653, 2014.

[46] P. Singh and B. Khan, "Smart microgrid energy management using a novel artificial shark optimization," *Complexity*, vol. 2017, pp. 1–22, 2017.

[47] M. Abdullahi and M. A. Ngadi, "Correction: hybrid symbiotic organisms search optimization algorithm for scheduling of tasks on cloud computing environment," *PLoS ONE*, vol. 11, no. 8, 2016.

[48] D. Birla, R. P. Maheshwari, H. O. Gupta, K. Deep, and M. Thakur, "Application of random search technique in directional overcurrent relay coordination," *International Journal of Emerging Electric Power Systems*, vol. 7, no. 1, pp. 1–16, 2006.

[49] M.-Y. Cheng and D. Prayogo, "Symbiotic organisms search: a new metaheuristic optimization algorithm," *Computers & Structures*, vol. 139, pp. 98–112, 2014.

[50] Dipti, *Hybrid genetic algorithms and their applications [Ph.D. thesis]*, Department of Mathematics, Indian Institute of Technology Roorkee, Roorkee, India, 2007.

[51] M. Thakur, *New real coded genetic algorithms for global optimization [Ph.D. thesis]*, Department of Mathematics, Indian Institute of Technology Roorkee, Roorkee, India, 2007.