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Nature-Inspired Whale Optimization Algorithm for Optimal Coordination of Directional Overcurrent Relays in Power Systems

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Abstract: In power systems protection, the optimal coordination of directional overcurrent relays (DOCRs) is of paramount importance. The coordination of DOCRs in a multi-loop power system is formulated as an optimization problem. The main objective of this paper is to develop the whale optimization algorithm (WOA) for the optimal coordination of DOCRs and minimize the sum of the operating times of all primary relays. The WOA is inspired by the bubble-net hunting strategy of humpback whales which leads toward global minima. The proposed algorithm has been applied to six IEEE test systems including the IEEE three-bus, eight-bus, nine-bus, 14-bus, 15-bus, and 30-bus test systems. Furthermore, the results obtained using the proposed WOA are compared with those obtained by other up-to-date algorithms. The obtained results show the effectiveness of the proposed WOA to minimize the relay operating time for the optimal coordination of DOCRs.

Keywords: directional overcurrent relay coordination (DOCR); heuristic algorithm; plug setting (PS); time dial setting (TDS); whale optimization algorithm (WOA)

1. Introduction

1.1. Motivation and Incitement

In an electrical power system, the protection strategy is an essential prerequisite for the proper functioning of the electrical system in a consistent manner. A worthy protection strategy clears a fault as soon as possible to preserve the supply of power to the healthy parts of the system unaffected by the fault. Every device of an electrical power network is safeguarded by two types of protection, i.e., primary and backup protection. For a robust configuration of an electrical power network, the primary protection for a fault should respond as quickly as possible to isolate the faulty area from the rest of the system. However, if the primary network defense is unsuccessful in clearing the fault, the secondary protection should take over the responsibility for clearing the fault. This should be the preferred scenario of any defensive strategy because the primary defense isolates only the affected area whereas, whenever the secondary reinforcement functions, a greater portion of the network has to suffer needlessly from power outages. For guaranteeing that only the affected section of the system is isolated in this manner while reducing the probability of undesirable blackouts, a reliable and effective management of the protection equipment is required. An effective and profitable protection strategy for a multi-loop electrical power network requires the inclusion of directional overcurrent relays (DOCRs). The functionality and configuration of DOCRs is determined by two constraints: time dial setting (TDS) and plug setting (PS). As a result of the appropriate coordination of DOCRs, the TDS and PS of the DOCRs are controlled such that the extent of the fault is removed by the primary protection as consistently and quickly as possible. Moreover, the mutual setup of any DOCRs should be managed appropriately with other DOCRs to protect the neighboring devices As a result of this scheme, the coordination problem can become significantly complicated.

1.2. Literature Review

To clarify this complicated issue, numerous techniques have been established in the literature. In [1], the curve intersection methodology was used to solve the coordination problem of overcurrent relays. In [2], the setting of relays was determined with a graphical selection process. In [3], an expert system was used that utilizes the minimum break point set. Other techniques include sequential programming [4] and linear theory [5].

Recently, nature-inspired optimization methods have been developed in the literature to explain the complex problems within the electrical power network, including the DOCR coordination problem [6–10]. In [11,12], the optimal DOCR design was determined with respect to the changing topological arrangement of the system. In [13,14], a hybrid genetic algorithm for DOCR coordination was applied to reveal the optimum TDS and PS values of DOCRs considering the line or generation unit outage contingencies. The outages of any line or generator is considered as an N-1 contingency according to NERC reliability standards [15]. In [16,17], N−1 contingency analysis has been widely considered in power system planning studies. In [18,19], the DOCRs problem was solved in a multi-loop transmission system deliberating all promising system topologies generating from single line outage contingencies. In [20], the optimal protection coordination was solved by considering the maximum DG penetration level. However these alterations in the network configuration might cause improper operation of the protection scheme. In [21], the protection coordination problem was solved by fault current limiters accommodating both grid-connected and islanded modes of operation without considering line or DG outage. In [22], the protection coordination problem was solved for micro-grids by incorporating a new set of coordination constraints that correspond to line, substation, and DG outages, as well as micro-grid operation modes. Moreover all of these network topologies lead to the complexity of the problem, as well as result in mis-coordination of DOCRs, constantly leading to contingencies. To overcome this issue and reduce the power outages it has been highly recommended for the relay settings to be determined optimally considering only the main system configuration [23–26]. In [27], the coordination of DOCRs was determined by a linear method. In [28,29], the coordination issue is expressed as a mixed integer nonlinear programming (MINLP) issue, and was solved using different population-based optimization algorithms. In [30,31], several bio-inspired algorithms were developed to solve the DOCR coordination issue by designing a linear formulation. In [32–36], a different version of particle swarm optimization (PSO) was used to determine the optimum values for DOCRs. A different version of the differential algorithm was reported in [37] to solve the DOCR coordination problem to point out the superiority of modified differential evolution algorithms. In [38], the grey wolf optimizer (GWO) algorithm was suggested to solve the optimum DOCR coordination problem. In [39], a teaching learning-based optimization (TLBO) algorithm was suggested for DOCR coordination. In [40], biogeography-based optimization (BBO) was used. In [41], back tracking algorithm was used for DOCR coordination problem. A mixed integer linear programming (MILP) approach was used in [42]. In [43], the firefly (FA) metaheuristic and [44] modified electromagnetic field optimization (MEFO) optimizations were used for DOCR coordination. In [45], a modified form of teaching-based optimization was used. In [46], an analytic approach was used to address the DOCR problem. In [47], an improved group search was used in relay coordination. In [48], a comparative study of different metaheuristic algorithms was performed to address the DOCR problem. In [49], multiple embedded crossover PSO was used for DOCR coordination. The DOCR problem in a multisource network could be illustrated as an optimization issue in electrical power systems. The drawback of the previous optimization techniques, as well as the metaheuristic optimizations, is the prospect of merging standards that may not be optimal in all instances, but instead are confined to a local optimal value. To comprehend this problem, a WOA algorithm strategy is inspected in this investigation to determine the precise and optimal DOCR coordination in relation to other up-to-date algorithms.

1.3. Contribution and Paper Organization

In this paper, the optimal coordination of DOCRs was determined by a nature-inspired whale optimization algorithm (WOA) deployed in a multi-loop power system. The WOA is inspired by the Humpback whales' strategy for apprehending prey using the bubble-net hunting approach, a cooperative feeding method used by groups of humpback whales as they blow bubbles to encircle and corral their prey. The suggested WOA has extraordinary exploration competency and speed as compared to other meta-heuristic techniques [50,51]; this characteristic makes the population members of WOA more discriminative when searching for the optimal solution compared to other meta-heuristic algorithms. The primary aim of our proposed WOA is to determine the optimal values of TDS and PS to minimalize the operational period of DOCRs with respect to backup and relay setting restrictions. The remaining of this paper is organized as follows. Section 2 describes the DOCR problem formulation. The proposed WOA is presented in Section 3. Section 4 elaborates on the simulation results for different IEEE test systems with other reported methods. Section 5 summarizes all simulation results with previous techniques. The conclusions are stated in Section 6.

2. DOCR Problem Formulation

The key objective of DOCR coordination is to sense the fault and detach the affected sections as quickly as possible. To achieve this goal in relay coordination, optimum settings for TDS and PS of each DOCR must be established. The aim is to minimize the total operating time of all primary DOCRs by satisfying the distinct constraints, as defined by the objective function (OF) (Equation (1)):

$$\min f = \sum_{i=1}^{n} T_{i,j}, \tag{1}$$

where $T_{i,j}$ is the operational time of the primary relay for a fault at zone j. In this way, the distinctive curve for working relay R_i is chosen from a selected portion of the decisions of the IEC standard as follows (Equation (2)):

$$T_{op} = \text{TDS}_i \left(\frac{\alpha}{\left(\frac{\text{IF}_i}{\text{PS}\times\text{CTR}} \right)^k - 1} \right), \tag{2}$$

where α and k are constants having values α = 0.14 and k = 0.02, and TDS, IF, PS, and CTR are the time dial setting, fault current, plug setting, and current transfer ratio (CTR) for normal inverse type relays, respectively. Figure 1 portrays the schematic outline for the coordination of DOCRs in an electrical power network.

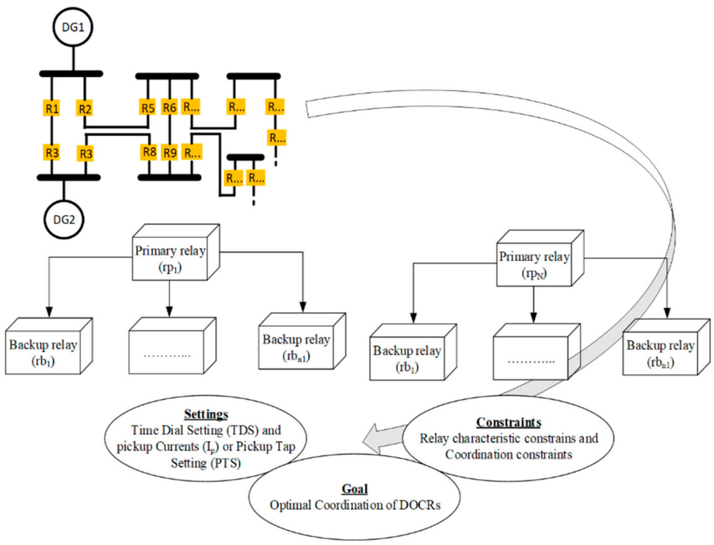

Figure 1. Schematic outline for DOCR coordination in an electrical power network.

2.1. Coordination Criteria

In an electrical protection scheme, the primary/backup safety pattern needs to be simultaneously coordinated by coordination time interval (CTI). The value of the CTI could vary from 0.2–0.5 s, depending upon different circumstances and factors. The preceding can be written as:

$$T_b \geq T_p + \text{CTI}, \tag{3}$$

where:

T_b: the backup relay operating time; and
T_p: the primary (or main) relay operating time.

2.2. Relay Setting Bounds

The overall working time can be minimized under two imperatives: the requirements of relay restriction and coordination limitations. The main requirements define the limits of TDS and PS, while alternate imperatives are related to the coordination of primary/backup relays. The limits on relay setting parameters are dependent on relay limitations and design, and their ranges can be expressed as follows:

$$\text{TDS}_i^{min} \leq \text{TDS}_i \leq \text{TDS}_i^{max}, \tag{4}$$

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

3. Whale Optimization Algorithm

The whale optimization algorithm (WOA) was developed by Mirjalili in 2016 [50] as a novel nature-inspired heuristic technique to solve problems related to engineering and different mathematical optimization issues. The common behaviors of humpback whales are the basis of WOA. This optimization technique is inspired by the bubble net hunting approach of humpback whales as they follow a circular shaped route for hunting small fish near the surface. This feeding process is a distinctive behavior of humpback whales, making this optimization unique among other nature-inspired optimization methods. To design the mathematical model of WOA, three steps are involved in the bubble-net hunting process. The first step is the encircling of the prey, the second step is a spiral bubble-net feeding movement, and the third step is the search for prey. All steps are described in detail below.

3.1. Encircling Prey

The position of the target and prey is recognized and surrounded by the humpback whales. Since the optimal strategy for locating the prey in the search area is not characterized by all of the whales at first, the existing best candidate guidance is supposed to be revealed by the entity closest to the optimum plan. By characterizing the best search agent, other search agents are updated in the direction of the best search agent. This plan can be illustrated as:

$$\vec{E} = \left|\vec{C} \cdot \vec{Z}^{*}_{|t|} - \vec{Z}_{|t|}\right|, \tag{6}$$

$$\vec{Z}^{*}(t+1) = \vec{Z}^{*}_{(t)} - \vec{A} \cdot \vec{D}, \tag{7}$$

where t is the current iteration; $\vec{Z}^{*}$ denotes the provided best solution in the position vector $\vec{Z}$; and $\vec{A}$ and $\vec{C}$ are the coefficient vectors. It should be noted that $\vec{Z}^{*}$ will be amended in each iteration, where $\vec{D}$ is the distance of ith whale to the prey. In addition the vectors $\vec{A}$ and $\vec{C}$ are calculated as in Equations (8) and (9), respectively, as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a}, \tag{8}$$

$$\vec{C} = 2 \cdot \vec{r}, \tag{9}$$

where $\vec{r}$ is arbitrarily nominated vector having a range between zero and one, while, for the exploitation and exploration steps, the value of a is reduced from two to zero.

3.2. Bubble-Net Attacking Method

To model this strategy, two techniques employed by humpback whales are presented below.

3.2.1. Shrinking Encircling Mechanism

$\vec{A}$ decrease in the estimation of a from two to zero through the iterations of Equation (7) results in this conduct. Likewise, by diminishing the value of a, which is a randomly chosen value in $[-a, a]$, the change scope of $\vec{A}$ is additionally decreased. The original location of search agents is chosen amongst the primary location of every agent and position of the best agent by picking irregular qualities for $\vec{A}$ in the interval [−1, 1].

3.2.2. Spiral Updating of Position

In this process, the separation between the whale positioned at (Z, W) and prey positioned at (Z^*, W^*) is determined. From that point forward, for mimicking the spiral-shaped movement of humpback whales, a helix condition is composed amongst the whale location and prey location as:

$$\vec{Z}(t+1) = \vec{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{Z}^{*}(t), \tag{10}$$

where $\vec{D}'$ determines the location or distance of whale i to the prey and can be obtained as $D^{\rightarrow\prime} = \left|\vec{D}' \cdot e^{bl} \cdot \cos|2\pi l|\right|$. Furthermore, b is a constant to represent the state of the logarithmic helix, and l is an arbitrary number in the range [−1, 1]. In view of the concurrent swimming of humpback whales around the prey in a contracting loop and following a helix formed path, the equal likelihood of choosing either the shrinking surrounding technique or the helix strategy can be summarized as:

$$\vec{Z}(t+1) = \begin{cases} \vec{Z}\{t - \vec{A}.\vec{D} & \text{if } p \leq 0.5 \\ \vec{D}' \cdot e^{bl} \cdot \cos\{2\pi l + \vec{Z}^*\{t & \text{if } p \geq 0.5 \end{cases}, \quad (11)$$

where p is an arbitrary number having a range between zero and one.

3.3. Search for Prey

An equivalent technique dependent on the heterogeneity of the vector $\vec{A}$ can be utilized when searching for the prey (exploration). An arbitrary survey of humpback whales shows that they are in view of one another and distinguishable. In like manner, a moving search agent far from a reference whale is expected to be skilled in the behavior, where $|\vec{A}| > 1$. Additionally, the situation of a search agent in the exploration stage is updated in view of an arbitrary search agent rather than the best pursuit agent originated up until this point. The mathematical model can be expressed as:

$$\vec{D} = \left|\vec{C} \cdot \vec{Z}^*_{\text{rand}} - \vec{Z}\right|, \quad (12)$$

$$\vec{Z}(t+1) = \vec{Z}_{\text{rand}} - \vec{A} \cdot \vec{D}. \quad (13)$$

3.4. The Steps of WOA

The principal procedures of WOA are as follows: The WOA starts with an established set of randomly-created results. The locations of pursuit agents, considering an arbitrary determination of hunt agent or the given best result, are then updated. For exploration and exploitation, parameter "a" is reduced from two to zero. When $|\vec{A}| > 1$, an arbitrary hunt agent is chosen, and when $|\vec{A}| < 1$, the best result is chosen for updating the positions of the pursuit agents. This enhancement strategy can modify the movement among spiral and circular movements depending on the measure of p. Finally, the WOA is stopped when the criteria are met. Algorithm 1 depicts the pseudocode of the WOA. In addition, the flowchart of WOA is given in Figure 2.

Algorithm 1. The pseudocode of WOA.
Initialize population size (NP), number of design variables and meeting criteria, number of fitness function evaluations
Analyze the fitness function value for each search agent
X^* = The best search agent
while (t < maximum number of iteration)
for each search agent
Update a, $\vec{A}$, C, l and p
if ($p < 0.5$)
if ($|\vec{A}| < 1$)
Update the position of the current search agent by the Equation (6)
else if ($|\vec{A}| \geq 1$
Select the random search agent X_{rand}
Update the position of the current search agent by the Equation (13)
end if
else if ($p \geq 0.5$)
Update the position of the current search agent by the Equation (10)
end if
end for
Alleviate any search agent that goes outside the search space
fitness function evaluations of each search agent
Update X^* if there is a better solution
$t = t + 1$
end while
Return X^*

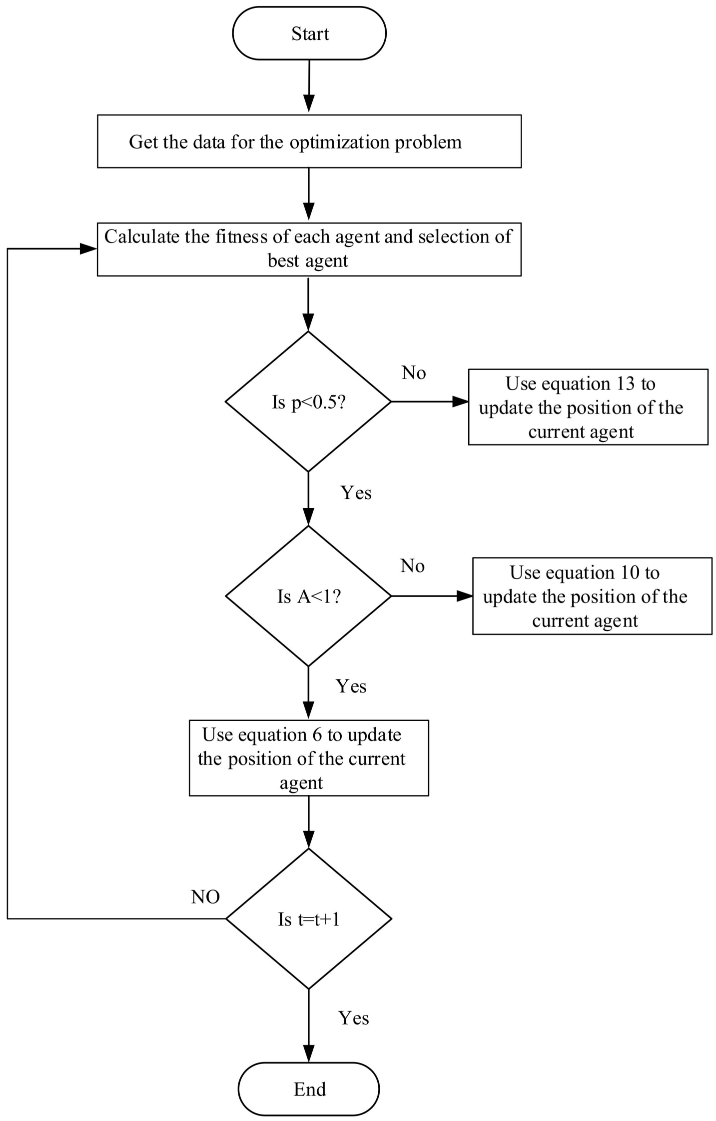

Figure 2. The flowchart of whale optimization algorithm (WOA).

4. Results and Discussion

In this section, we report that the suggested WOA used to manage the DOCR coordination problem has been confirmed and successfully tested for six case studies: the IEEE 3-, 8-, 9-, 14-, 15-, and 30-bus systems. The results have been obtained by developing an accurate simulation program using MATLAB software @R2018b (Mathworks, Natick, MA, USA).

4.1. Case I: IEEE Three-Bus System

The suggested algorithm is verified on an IEEE three-bus system. The details of this test system can be found in [28]. This system consists of three lines and six DOCRS as presented in Figure 3. The proposed settings for CT ratios and pickup tap settings are shown in Table 1. It is assumed that the pickup tap setting is a discrete variable between 1.25 and 5.0 in steps of 0.5, and the ranges of lower and upper TDS are set at 0.05 and 1.1, respectively. The coordination interval to be considered is 0.3 s. To create a perfect assessment, a three-phase short circuit current is replicated in the central of lines [28] and, hence, is not repeated here. The optimal TDS and PS values achieved by the proposed algorithm are tabulated in Table 2. Table 3 shows the relative result of the proposed algorithm in comparison to other published techniques reported in the literature. It was observed that the suggested WOA accomplishes a better result as compared to other methods. The overall net gain in time obtained by the suggested WOA is depicted in Table 4, which shows the superiority of the WOA over other methods explained in the literature. Figure 4 depicts the WOA convergence characteristic obtained during the course of the simulation.

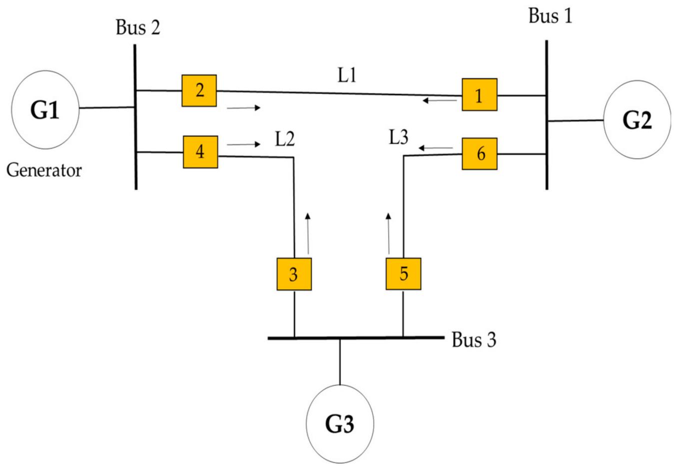

Figure 3. The IEEE three-bus system.

Table 1. Proposed setting for the IEEE three-bus system.

Relay No.	CTR	Pickup Tap
1	300/5	5
2	200/5	1.5
3	200/5	5
4	300/5	4
5	200/5	2
6	400/5	2.5

Table 2. Optimal TDS for the IEEE three-bus system.

Relay No.	TDS	PS
1	0.0500	1.2500
2	0.0500	1.2500
3	0.05553	1.3837
4	0.0500	1.2500
5	0.0710	2.4746
6	0.1587	2.2163
Total Operating Time (s)		1.5262

Table 3. Comparison of the WOA result with the literature for the IEEE three-bus system.

Method	Objective Function
TLBO (MOF) [39]	6.972
TLBO [39]	5.3349
MDE [37]	4.7806
Simplex method [29]	1.9258
MINLP [28]	1.727
Seeker algorithm [28]	1.599
PSO method [34]	1.9258
BB0-LP [40]	1.59871
GSO [47]	1.4807
Proposed algorithm	1.5262

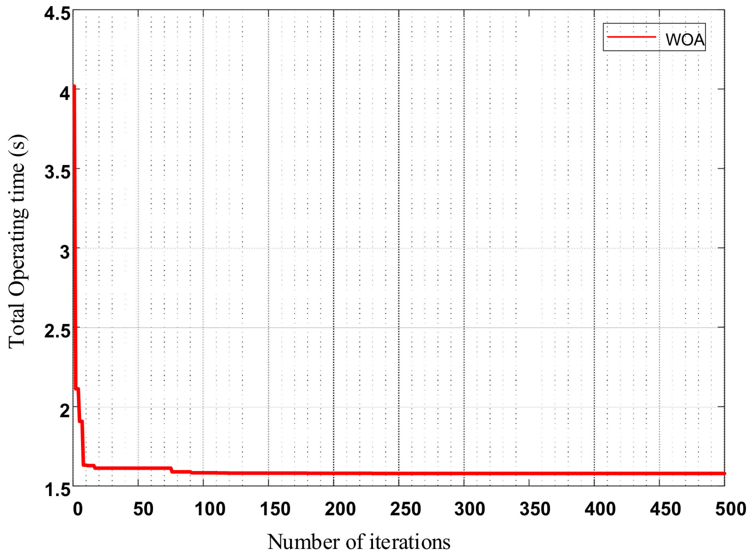

Figure 4. Convergence characteristic of WOA for Case I.

Table 4. Comparison of total net gain in time achieved by WOA with the methods used in the literature for IEEE three-bus system.

Net Gain	$\sum \Delta(t)$ (s)
WOA/TLBO (MOF)	5.4458
WOA/TLBO	3.8087
WOA/MDE	3.2544
FWOA/SM	0.3996
WOA/MINLP	0.2008
WOA/SA	0.0728
WOA/PSO	0.3996
WOA/BBO-LP	0.07251

4.2. Case II: IEEE Eight-Bus System

The effectiveness and the performance of the suggested WOA is successfully tested on the IEEE eight-bus system. The information about the eight-bus test network is specified in [28]. This network comprises seven lines and 14 OCRs as presented in Figure 5, and has 28 design variables and 20 constraints. The proposed settings for current transformer ratio for the IEEE eight-bus system are shown in Table 5. The lower and upper limits of TDS are set to 0.1 and 1.1, respectively, and seven discrete pickup tap settings are assumed (i.e., 0.5, 0.6, 0.8, 1.0, 1.5, 2.0, and 2.5). A CTI of 0.2 s is also assumed. To create a perfect assessment, a deliberate three-phase short circuit current is reported in [28]; hence it is not repeated here. The optimal TDS and PS for DOCRs obtained by the suggested WOA are shown in Table 6, while Table 7 depicts the relative comparison of the suggested WOA with other published techniques explained in the literature. As shown in Table 7, the suggested WOA has obtained an improved result for the above stated IEEE eight-bus system. The assessment of total net gain in time obtained in this case by the suggested WOA is shown in Table 8 with respect to other evolutionary algorithms mentioned in the literature. It was observed that the WOA algorithm has an advantage of net gain in time over other techniques and shows satisfactory and improved results. Figure 6 depicts the convergence characteristic of the WOA achieved during the course of the simulation.

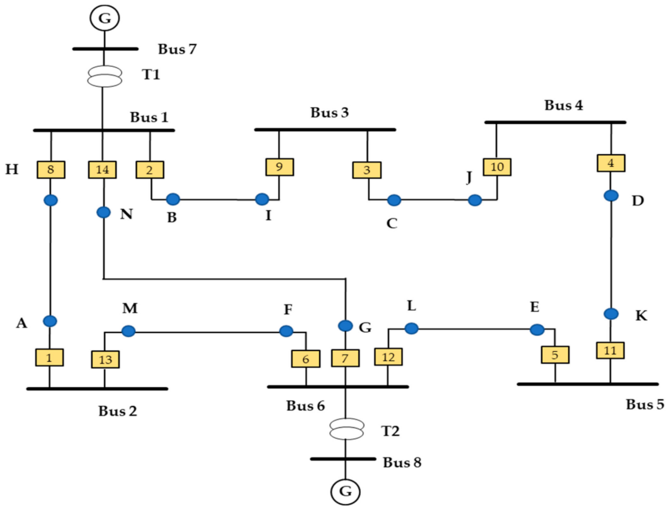

Figure 5. The IEEE eight-bus system.

Table 5. Current transformer ratio of the IEEE eight-bus system.

Relay No.	CTR
1	1200/5
2	1200/5
3	800/5
4	1200/5
5	1200/5
6	1200/5
7	800/5
8	1200/5
9	800/5
10	1200/5
11	1200/5
12	1200/5
13	1200/5
14	800/5

Table 6. Optimal TDS for the IEEE eight-bus system.

Relay No.	TDS	PS
1	0.1000	1.25
2	0.5929	1.3746
3	0.1007	1.2586
4	0.1000	1.25
5	0.3581	2.0638
6	0.2490	1.5745
7	0.1018	1.2726
8	0.3430	1.8559
9	0.1000	1.25
10	0.1000	1.25
11	0.1004	1.2548
12	0.1521	1.901
13	0.1000	1.25
14	0.1000	1.25
Total operating time (s)		5.9535

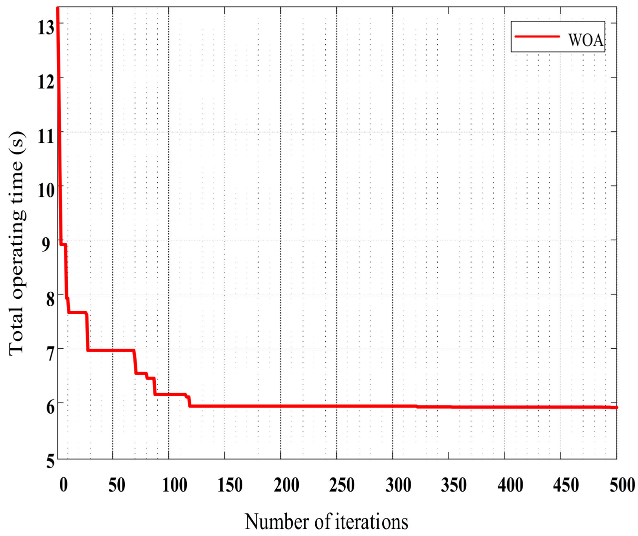

Figure 6. Convergence characteristic of WOA for case 2.

Table 7. Comparison of the WOA result with the methods used in the literature for the IEEE eight-bus system.

Method	Objective Function
SA [28]	8.4270
GA [14]	11.001
HGA-LP [14]	10.9499
NLP [2]	6.4169
LM [2]	11.0645
BBO-LP [40]	8.75559
MILP [42]	8.0061
FA [43]	6.6463
MEFO [44]	6.349
BSA [41]	6.363
Proposed algorithm	5.9535

Table 8. Comparison of total net gain in time achieved by WOA with the methods used in the literature for the IEEE eight-bus system.

Net Gain	$\sum \Delta(t)$ (s)
WOA/SA	2.4735
WOA/GA	5.0475
WOA/HGA-LP	4.9964
WOA/NLP	0.45819
WOA/LP	5.111
WOA/BBO-LP	2.8020
WOA/FA	0.6929
WOA/MEFO	0.3955
WOA/BSA	0.4095

4.3. Case III: IEEE Nine-Bus System

The third framework deliberated in this paper is the IEEE nine-bus test system as shown in Figure 7. This conveyance framework comprises nine buses and 12 lines and is powered by a generator associated with bus 1. The short circuit test estimated for primary/back up OCRs is given in reference [13] and, thus, is not revisited here. The proposed setting value for the current transformer proportion is 500/1 for all OCRs. The lower and higher estimates of TDS are set to 0.1 and 1.2, respectively. The lower and higher estimates of PS are set to 1.5 and 2.5, respectively. A coordination interval of 0.2 s is considered.

The optimum values for TDS and PS of the DOCRs obtained by WOA are shown in Table 9. Table 10 depicts the relative result of the suggested WOA with other published algorithms cited in the literature. As indicated by Table 10, the suggested WOA has accomplished a superior result when compared with different algorithms referred to in the literature. The examination of the complete net gain in time obtained for this illustration by the suggested WOA is shown in Table 11. It is seen that the WOA algorithm has promising advantages of net gain in time over other algorithms. Figure 8 delineates the convergence characteristic of WOA obtained during the simulation.

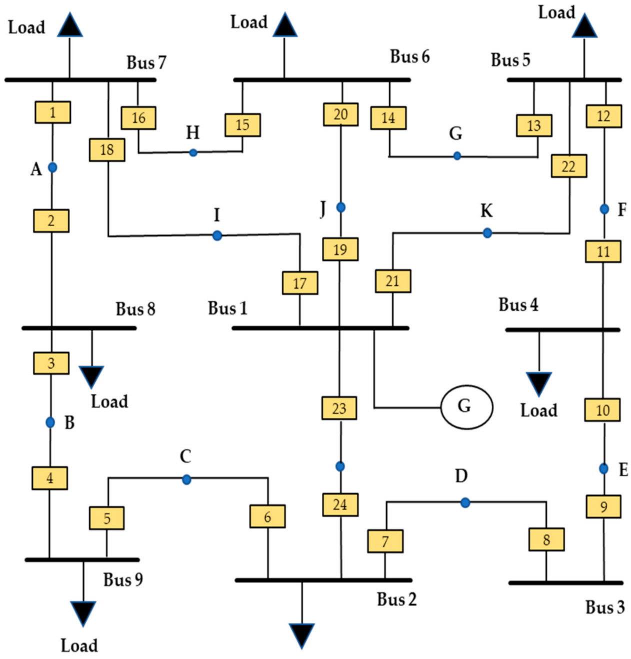

Figure 7. The IEEE nine-bus system.

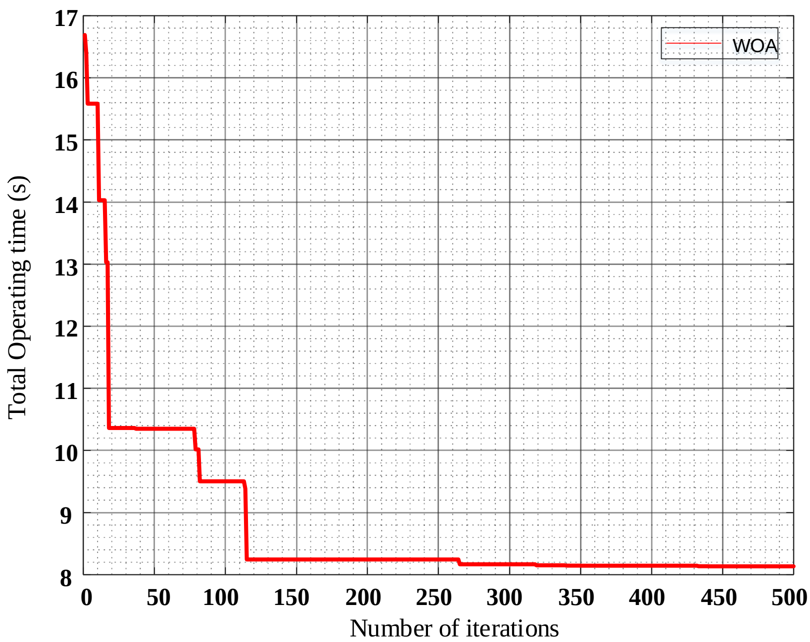

Figure 8. Convergence characteristic of WOA for Case 3.

Table 9. Optimal TDS for the IEEE nine-bus system.

Relay No.	TDS	PS
1	0.2316	2.4466
2	0.1001	1.5014
3	0.2377	2.4650
4	1.200	2.5000
5	0.1469	2.2553
6	0.7059	2.5000
7	0.1761	2.4542
8	0.5674	2.4224
9	1.2000	2.5000
10	0.2193	2.3922
11	0.6990	1.8076
12	0.1368	1.8399
13	0.1454	2.1276
14	0.1497	2.5000
15	0.1632	2.0901
16	1.1431	2.3815
17	0.2636	1.6991
18	0.14875	2.2135
19	0.12251	1.8376
20	0.18656	2.4963
21	0.51479	1.5402
22	0.17653	2.5000
23	1.2000	2.5000
24	0.1303	1.9311
Total operating time (s)		8.3849

Table 10. Comparison of the WOA result with the methods used in the literature for the IEEE-9 bus system.

Method	Objective Function
TLBO [45]	82.9012
IDE [45]	59.6471
MTALBO [45]	41.9041
GA [13]	32.6058
BBO [40]	28.8348
BH [44]	25.884
NPL [13]	19.4041
PSO [48]	13.9742
HS [44]	9.838
DE [48]	8.6822
Proposed algorithm	8.3849

Table 11. Comparison of total net gain in time achieved by the WOA with the methods used in the literature for the IEEE nine-bus system.

Net Gain	$\sum \Delta(t)$ (s)
WOA/TLBO	74.5163
WOA/IDE	51.2622
WOA/MTALBO	33.5192
WOA/GA	24.2209
WOA/BBO	20.4499
WOA/BH	17.4991
WOA/NPL	11.0192
WOA/PSO	5.5893
WOA/HS	1.4531
WOA/DE	0.2973

4.4. Case IV: IEEE 15-Bus System

The proposed technique is actualized over the IEEE-15 bus framework. This test framework is a highly distributed generator (DG) augmented distribution network comprising 21 lines and 42 DOCRs as shown in Figure 9, and it has 84 design variables and 82 imperatives. Additionally, the three-phase short circuit framework details can be found in [28]. The proposed setting for current transformer ratios and primary/backup relationships for the relays is shown in Table 12. The lower and upper limits of TDS and PS are set to 0.1 and 1.2, and 0.5 and 2.5, respectively. A coordination interval of 0.3 s is considered. The optimal TDS and PS for DOCRs accomplished by the suggested WOA are given in Table 13, while Table 14 shows the relative outcome of the suggested WOA with an already-published algorithm. The convergence characteristic for the overall operational period of the 15-bus system during the simulation is shown in Figure 10, which indicates that the convergence is quicker and yields an improved value for the objective function in fewer iterations. The advantage in overall net gain in time obtained by the suggested WOA is presented in Table 15, showing the dominance of the WOA algorithm over recent published methods.

Table 12. Current transfer ratio for the relay of the IEEE 15-bus system.

Relay No.	CT Ratio
18-20-21-29	1600/5
2-4-8-11-12-14-15-23	1200/5
1-3-5-10-13-19-36-37-40-42	800/5
6-7-9-16-24-25-26-27-28-31-32-33-35	600/5
17-22-30-34-38-39-41	400/5

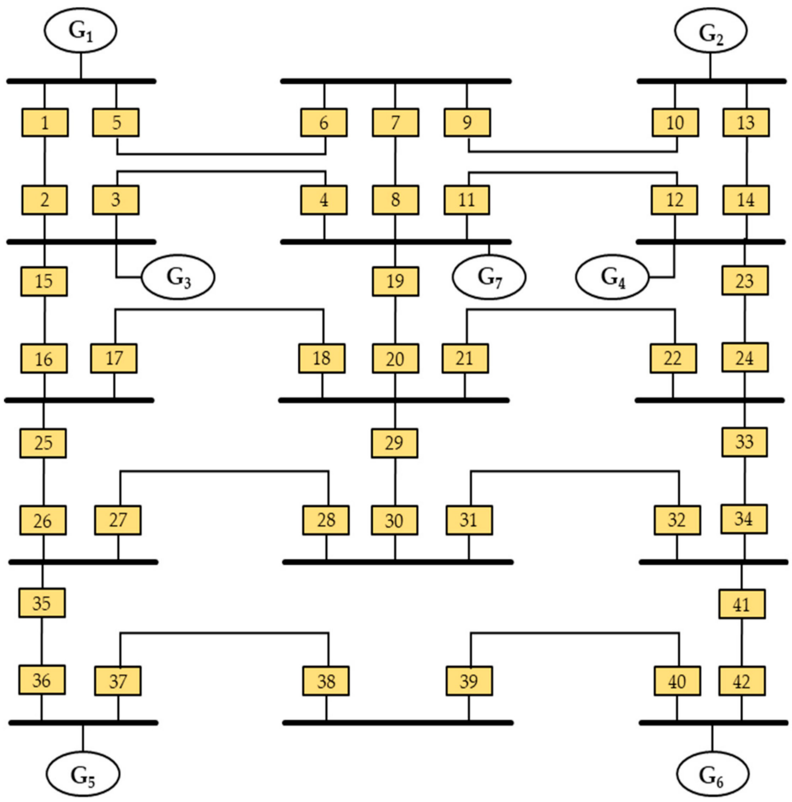

Figure 9. Diagram of the IEEE 15-bus system.

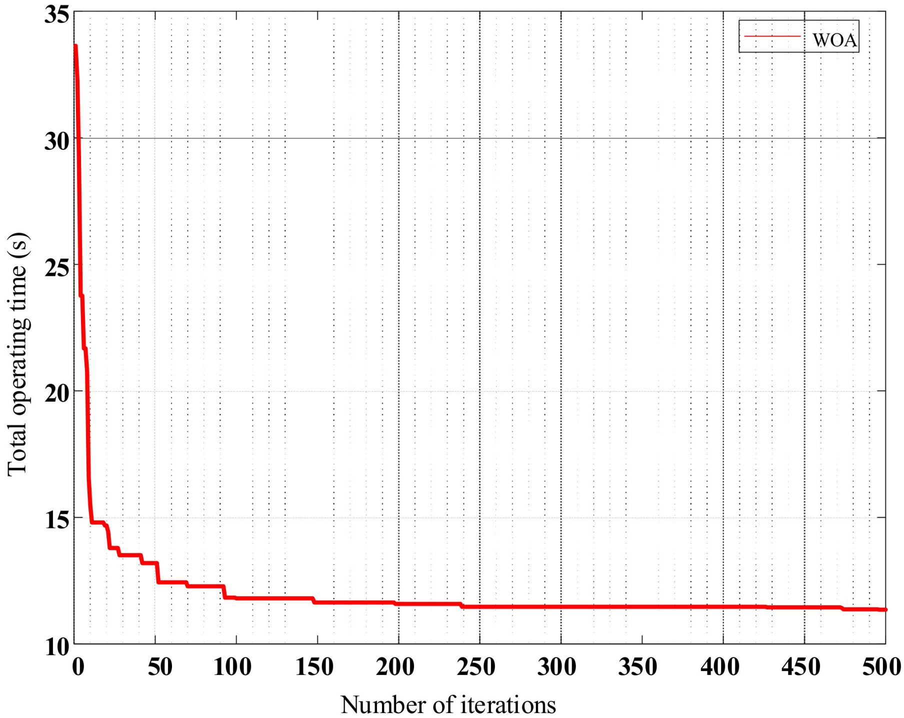

Figure 10. Convergence characteristic of WOA for Case 4.

Table 13. Optimal TDS for the IEEE 15-bus system.

Relay No.	WOA		Relay No.	WOA	
	TDS	PS		TDS	PS
1	0.1000	0.5000	22	0.1039	0.5195
2	0.1030	0.5150	23	0.1010	0.5049
3	0.1078	0.5393	24	0.1000	0.5000
4	0.1000	0.5000	25	0.1139	0.5695
5	0.1041	0.5206	26	0.1101	0.5504
6	0.1240	0.6201	27	1.0414	2.3668
7	0.1000	0.5003	28	0.3260	1.1297
8	0.1000	0.5000	29	0.2249	0.7461
9	0.1455	0.7275	30	0.1000	0.5000
10	0.1078	0.5392	31	0.1483	0.5000
11	0.1020	0.5103	32	0.1056	0.5280
12	0.1000	0.5000	33	0.1487	0.7438
13	0.1070	0.5350	34	0.2123	0.5689
14	1.1000	2.5000	35	0.1152	0.5759
15	0.1000	0.5000	36	0.7140	1.6790
16	0.1148	0.5742	37	0.1245	0.6229
17	0.1015	0.5077	38	0.1066	1.1121
18	0.4930	1.4766	39	0.4113	0.9377
19	0.1539	0.7699	40	0.1515	0.7576
20	0.2644	0.9671	41	0.4033	0.9166
21	0.1557	0.7785	42	0.1105	0.5195
T_{op} (s)			11.2670		

Table 14. Comparison of the WOA result with the methods used in the literature for the IEEE 15-bus system.

Method	Objective Function
MTLBO [45]	52.5039
SA [28]	12.227
MINLP [28]	15.335
AP [46]	11.6542
GSO [47]	13.6542
IGSO [47]	12.135
DE [48]	11.7591
HS [48]	12.6225
MEFO [44]	13.953
BSA [41]	16.293
Proposed algorithm	11.2670

Table 15. Comparison of total net gain in time achieved by the WOA with the methods used in the literature for the IEEE 15-bus system.

Net Gain	$\sum \Delta(t)$ (s)
WOA/TLBO	41.2369
WOA/SA	0.96
WOA/MINPL	4.068
WOA/AP	0.3872
WOA/GSO	2.3872
WOA/IGSO	0.868
WOA/DE	0.4921
WOA/HS	1.3555
WOA/MEFO	2.686
WOA/BSA	5.026

4.5. Case V: IEEE 30-Bus System

Figure 11 illustrates the 33 kV part of the IEEE 30-bus network. The network is sustained by three 50 MVA, 132/33 kV transformers associated with buses 1, 6, and 13. Notwithstanding the focus of over three supplies, two distributed generators (DGs) associated with buses 10 and 15 are likewise providing power to the network. The data and information of the network is presented in [52]. The framework has 20 lines (L1, L2, . . . , L20) and is protected by 39 DOCRs (R1, R2, . . . , R39) having 64 essential reinforcement assortments amongst them. Table 16 demonstrates all the conceivable 64 assortments of the essential reinforcement connections amongst the 39 OCRs. The fault current going through the primary/backup OCRs for different close-end three-phase faults is specified in [52], and, hence, are not reported here. The CT ratio for each OCR is assumed as 500:1. The upper and lower limits of TDS and PS are set to 0.1 and 1.2 for TDS, respectively, and 1.5 and 2.5 for PS, respectively.

A coordination interval of 0.3 s is considered. It is to be noticed that, for this framework, a portion of the essential reinforcement connections has been disregarded while tackling the coordination issue. These essential reinforcement connections are 14, 17-4, 19-4, 28-34, 30-33, 31-34, 32-33, and 37-33. The purpose for this lies in the way that, for these assortments, the fault currents going through the associated backup OCRs are small resulting in a greater working time of the backup OCRs; subsequently, the minimum CTI conditions are always sustained for these combinations.

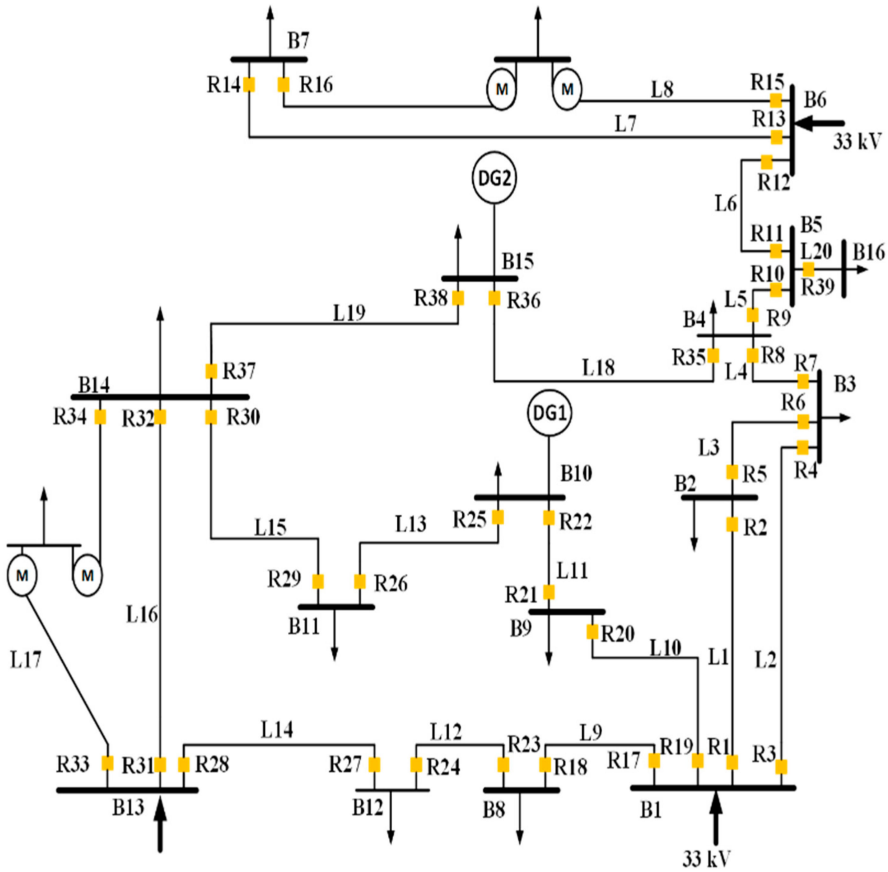

Figure 11. Diagram of the IEEE 30-bus system.

Table 16. Primary/backup relay pairs of the IEEE 30-bus system.

Fault Zone	Primary Relay	Primary Relay
L 1	1 2	4, 18, 20 6
L2	3 4	2, 18, 20 5, 8
L 3	5 6	1 3, 8
L 4	7 8	3, 5 10, 36
L 5	9 10	7, 36 12
L 6	11 12	9 -
L 7	13 14	11 15
L 8	15 16	11 13
L 9	17 18	2, 4, 20 24
L 10	19 20	2, 4, 18 22

Table 16. *Cont.*

Fault Zone	Primary Relay	Primary Relay
L 11	21 22	19 26
L 12	23 24	17 28
L 13	25 26	21 30
L 14	27 28	23 32, 34
L 15	29 30	25 31, 33, 38
L 16	31 32	27, 34 29, 33, 38
L 17	33 34	27, 32 37
L 18	35 36	29, 31, 38 7, 10
L 19	37 38	37 29, 31, 33
L 20	39 -	35 -

The optimal TDS and PS for DOCRs accomplished by the suggested WOA is specified in Table 17. Table 18 gives the relative result of the suggested WOA with other published algorithms cited in the literature. The convergence characteristic for overall operational time achieved for the 30 bus system in the simulation is presented in Figure 12, showing that the convergence is faster and yields an improved value for the objective function in less number iterations. The advantage in total net gain time obtained by the suggested WOA is presented in Table 19 that show the dominance of the WOA algorithm over recent published method.

Table 17. Optimal TDS for the IEEE 30-bus system.

Relay No.	TDS	PS
1	0.1131	1.6958
2	0.1000	1.5000
3	0.1007	1.5109
4	0.1007	1.5111
5	0.1000	1.5000
6	0.9236	2.4761
7	0.1000	1.5005
8	0.1000	1.5000
9	0.1001	1.5029
10	0.1002	1.5042
11	0.1076	1.6149
12	0.1000	1.5000
13	0.1074	1.6118
14	1.0933	2.4849
15	0.6461	2.3447
16	0.8541	1.9412
17	0.2737	1.7453
18	0.6984	2.1623

Table 17. *Cont.*

Relay No.	TDS	PS
19	0.1046	1.5824
20	0.2328	2.4762
21	0.1672	2.3334
22	0.1118	1.6782
23	0.1003	1.5000
24	0.1000	1.5000
25	0.1013	1.5205
26	0.1757	2.3145
27	0.1037	1.5555
28	0.2170	2.3228
29	0.1990	2.1887
30	0.2856	2.5000
31	0.3598	2.0241
32	0.1049	1.5747
33	0.1522	2.1039
34	0.1000	1.5006
35	0.2242	2.4661
36	0.1271	1.9075
37	0.1727	2.4772
38	0.2007	1.7111
39	0.1002	1.5035
Total operating time (s)		15.7139

Table 18. Comparison of the proposed WOA with the methods used in the literature for the IEEE 30-bus system.

Method	Objective Function
GA [48]	28.0195
PSO [48]	39.1836
DE [48]	17.8122
HS [48]	19.2133
SOA [48]	33.7734
Proposed Algorithm	15.7139

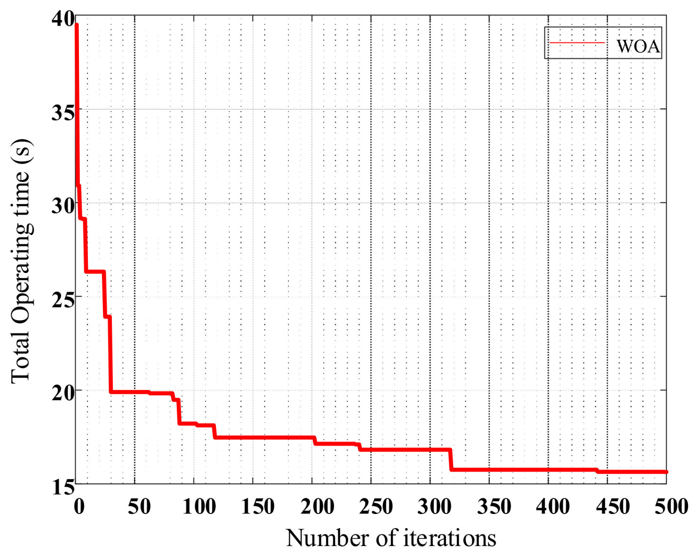

Figure 12. Convergence characteristic of WOA for Case 5.

Table 19. Comparison of total net gain in time achieved by the WOA with the methods used in the literature for the IEEE 30-bus system.

Net Gain	$\sum \Delta(t)$ (s)
WOA/GA	12.3056
WOA/PSO	23.4697
WOA/DE	2.0983
WOA/HS	3.4994
WOA/SOA	18.0595

4.6. Case VI: Coordination Scheme Using Numerical Directional Relays

This test framework is a highly distributed generator (DG) augmented distribution network comprising of 40 DOCRs as shown in Figure 13. Additionally, the three-phase short circuit framework and system details can be found in [53]. The proposed setting for current transformer ratios and for the relays is shown in Table 20. The lower and upper limits of TDS and PS are assumed as continuous and set in the range of [0.1, 1.1] and [0.5, 2] [54], and CTI is considered as 0.2 s, respectively.

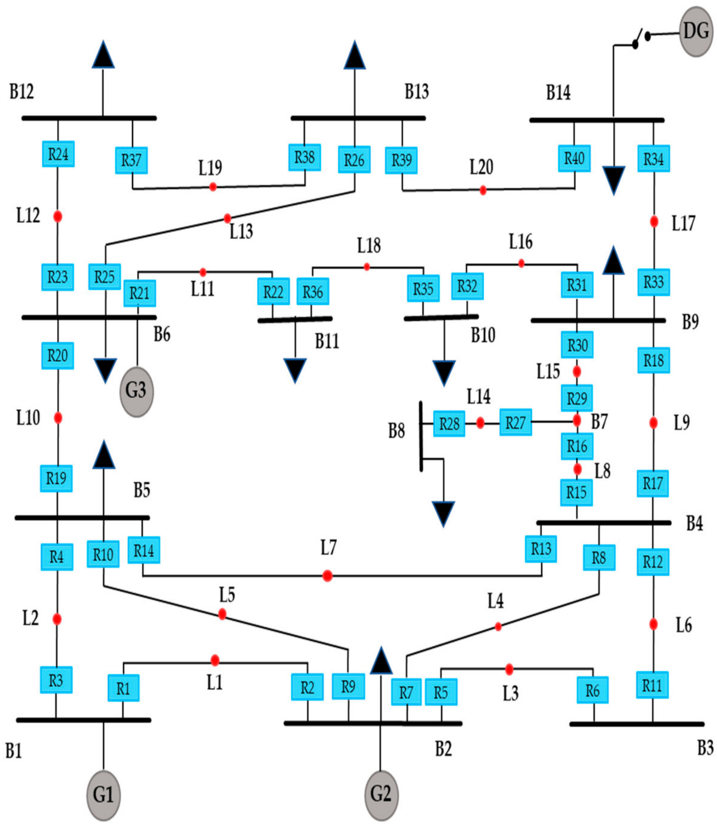

Figure 13. Diagram of the IEEE 14-bus system.

Table 20. Current transfer ratio for the relay of the IEEE 14-bus system.

CT Ratio	Relay No.	CT Ratio	Relay No.
8000/5	1	1000/5	20, 35, 38
5000/5	29	800/5	16,18
4000/5	5, 25	600/5	22, 32, 37, 40
3500/5	3, 14	500/5	17, 26, 34
3000/5	21	400/5	2, 4, 8, 10, 13, 24
2500/5	7	250/5	11
2000/5	12,36,39	200/5	6
1600/5	9, 19, 23, 27, 31	50/5	28
1200/5	15, 30, 33	-	-

Application of WOA

The objective function was utilized by the suggested WOA for numerical DOCRs with indistinguishable parameter as consider for the rest of case studies. The optimal TDS and PS obtained are given in Table 21, which shows that the WOA algorithm gives an optimum and best values and that it optimized the TDS, PS, and total operating time to optimal values. The objective function value obtained during the course of the simulation for the finest candidate arrangement in every iteration appears in Figure 14, which validates that the convergence is prompter and acquires the preeminent values in fewer iterations. Furthermore, for all the coordination conditions, the optimal value obtained by WOA for all numerical DOCRs will fulfill the coordination constraints. Moreover no desecration has been established regarding the coordination constraints. Table 22 provides the comparative results with previously published techniques, which validate the superiority of WOA over other optimization techniques. In all conditions, the WOA performed outstandingly in minimizing the overall operational time up to an optimal value and will maintain proper coordination as well during a fault condition. Table 23 shows the overall time gain accomplished by the suggested WOA, exhibiting the predominance and favorable circumstances of WOA over the algorithms specified in the references.

Table 21. Optimal TDS for the IEEE 14-bus system.

Relay No.	TDS	PS
1	0.1000	0.5000
2	0.1000	0.5000
3	1.0227	1.9967
4	0.1000	0.5000
5	1.1000	2.0000
6	1.0703	1.9461
7	0.1000	0.5000
8	0.1010	0.5048
9	0.1316	0.6582
10	0.2419	1.1192
11	0.1097	0.5486
12	0.1154	0.5773
13	0.1000	0.5000
14	1.0968	1.9941
15	0.1146	0.5731
16	0.1107	0.5539
17	0.1000	0.5001
18	0.5058	1.9887
19	1.0551	1.9185
20	0.1145	0.5727
21	0.2439	1.2169
22	0.1379	0.6897
23	0.2896	0.5218
24	0.2923	1.4617
25	0.3049	1.7079
26	1.1000	2.0000
27	0.1014	0.5071
28	0.1021	0.5108
29	0.1000	0.5000
30	0.8158	1.9280
31	1.0175	1.9850
32	1.0721	1.9508
33	0.1278	0.6390
34	0.1264	0.6324
35	0.1620	0.8101
36	1.0557	1.9810
37	0.1710	0.8283
38	0.2721	0.5000
39	0.9686	1.7611
40	0.13037	0.6518
Total operating time (s)		9.9105

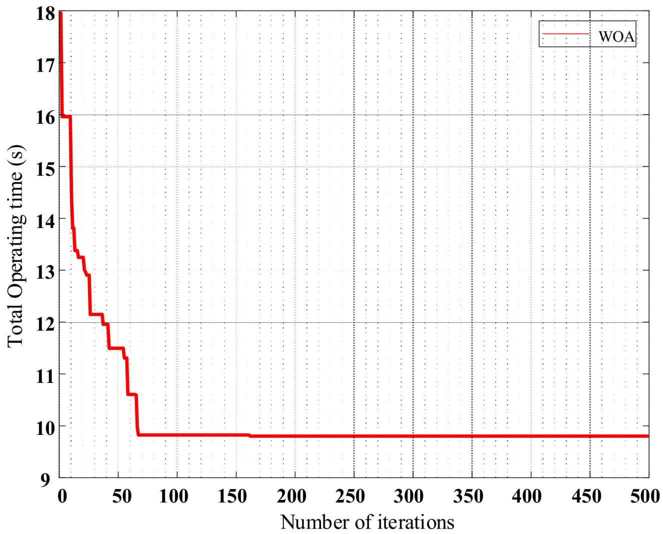

Figure 14. Convergence characteristic of WOA for the IEEE-14 bus system.

Table 22. Comparison of the proposed WOA with the methods used in the literature for the IEEE 14-bus system.

Method	Objective Function
HGA-LP [42]	13.4914
MILP [42]	13.1411
MECPSO [49]	12.919
MAPSO [49]	14.126
Proposed Algorithm	9.9105

Table 23. Comparison of total net gain in time achieved by the WOA with the methods used in the literature for the IEEE 14-bus system.

Net Gain	$\sum \Delta(t)$ (s)
WOA/HGA-LP	3.5812
WOA/MILP	3.2306
WOA/MECPSO	3.0085
WOA/MAPSO	4.2155

5. Discussion

The WOA algorithm was used to assess the DOCR coordination problem. The suggested algorithm has a high search capability and convergence speed compared to other algorithms, and these distinctive features make the search agents of the WOA more discriminative in finding the optimum result as compared to other algorithms. The case studies presented in this paper have also been evaluated by different optimization algorithms as shown in the literature, and an improved optimal solution was observed from the proposed WOA algorithm compared to these other algorithm options. The DOCR coordination problem is basically a highly constrained optimization problem. As the WOA can solve constrained and unconstrained optimization problems, the relay coordination problem has been converted into an unconstrained optimization problem by defining a new objective function and by using the boundaries on the TDS and PS (and boundaries on the relay operating time) as the limits of the variables. A systematic procedure for converting a relay coordination problem into an optimization problem has been developed in this paper. A program has been developed in MATLAB for finding the optimum time coordination of DOCRs using the WOA method. The program can be used for setting the optimum time coordination of DOCRs in a system with any number of relays and any number of primary-backup relationships. The TDS, PS, and total operating time of relays obtained for all case studies by the proposed WOA ensured that the DOCRs will activate in the minimum possible amount of time for a fault at any point in the system. However, if the number of relays is increased, the nature of the highly constrained problem becomes more distinct. Therefore, an accurate and optimum relay coordination minimizes the total operating time as well as reduces and limits the damage produced by the fault. Unwanted tripping of the circuit breakers can also be bypassed by this method. The convergence characteristic graphs obtained during simulations show that the convergence is faster and obtains a superior solution for the fitness function "Z" in fewer iterations. The WOA algorithm is superior to the TLBO (MOF), TLBO, MDE, SM, MINLP, SA, PSO, and BBO-LP algorithms, as shown in Table 4. The WOA algorithm gains 5.4458 s, 3.8087 s, 3.2544 s, 0.3996 s, 0.2008 s, 0.0728 s, 0.3996 s, and 0.07251 s over the TLBO (MOF), TLBO, MDE, SM, MINLP, SA, PSO, and BBO-LP algorithms in Case I, respectively. Although this may appear insufficient, it should be noted that it is a very small system. In Case II, the WOA algorithm gains 2.4735 s, 5.0475 s, 4.9964 s, 0.45819 s, 5.111 s, 2.8020 s, 0.6929 s, 0.3955 s, and 0.4095 over the SA, GA, HGA-LP, NLM, LM, BBO-LP, MILP, FA, MEFO, and BSA algorithms, respectively, as shown in Table 8. In Case III, the WOA algorithm gives an advantage of 74.5163 s, 51.2622 s, 33.5192 s, 24.2209 s, 20.449 s, 17.4991 s, 11.0192 s, 5.5893 s, 1.4531 s, and 0.2973 s over the TLBO, IDE, MTALBO, GA, BBO, BH, NPL, PSO, HS, and DE, respectively, as shown in Table 10. In Case IV, the WOA algorithm gives an advantage of 41.2369 s, 0.96 s, 4.068 s, 0.3872 s, 2.3872 s, 0.868 s, 0.4921 s, 1.3555 s, 2.686 s, and 5.026 over the TLBO, SA, MINPL, AP, GSO, IGSO, DE, HS, MEFO and BSA algorithms, respectively, as shown in Table 14. This advantage is sufficient given that it is a very large system. In case V the WOA again gains 12.3056 s, 23.4697 s, 2.0983 s, 2.0983 s, 3.4994 s, and 18.0595 s over the GA, PSO, DE, HS and SOA algorithms. In case 6 of numerical DOCRs the WOA gains 3.5812 s, 3.2306 s, 3.0085 s, and 4.2155 s over the HGA-LP, MILP, MECPSO, and MAPSO, respectively. For Case V, this advantage is more than sufficient given that it is a very large and complex system, as can be clearly seen from Tables 3, 7, 10, 14, 18 and 23 from Figures 4, 6, 8, 10, 12 and 14 the proposed method is superior to the recent published techniques mentioned in the literature in terms of the quality of the solution, convergence, and minimization of the objective function to the optimum value. Furthermore, the suggested technique addressed the weaknesses of the already published algorithms.

6. Conclusions

In this paper, the problem of optimally coordinating DOCRs was evaluated using a swarm-based optimizer that is inspired by the hunting behavior of humpback whales. The suggested WOA has three operators to simulate the search for prey, encircling the prey, and bubble-net foraging behavior of humpback whales. The optimum coordination problem of DOCRs has been expressed as a mixed integer nonlinear programing problem. In order to assess the performance of the proposed WOA, it has been applied to six different systems, which include the IEEE three-bus, eight-bus, nine-bus, 14-bus, 15-bus, and 30-bus test systems. The simulation results of the WOA algorithm efficiently minimize all six models of the problem. The performance of the WOA can be seen from the optimized minimum objective function values for each case studies. The results obtained validate that the proposed WOA is an effective and reliable tool for the coordination of directional overcurrent relays. Moreover, the results obtained using WOA are better than those obtained using a number of well-known and up-to-date algorithms stated in the literature.

In the future the proposed WOA will be implemented to solve the protection coordination problem for micro-grids both for grid-connected and islanded modes of operation that correspond to line, substation, and DG outages, as well as micro-grid operation modes. Moreover, as the current implementation is limited to three-phase faults only, we aim to implement our proposed scheme for single-phase and two-phase faults in the systems in future study.

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Nomenclature

OCR	Overcurrent relay
DOCR	Directional overcurrent relay
TDS	Time dial setting
T_{op}	Total operating time
PSM	Plug setting multiplier
I_f	Fault current
I_p	Pickup current
CTR	Current transformer ratio
CTI	Coordination time interval
DG	Distributed generation
IDMT	Inverse definite minimum time
IEC	International electro-technical commission
IEEE	Institute of electrical and electronics engineers
NERC	Federal energy regulatory commission
PR	Primary relay
BR	Backup relay
T_b	Backup relay operating time
T_p	Primary relay operating time
LP	Linear programming
NLP	Non-linear programming
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MECPSO	Multiple embedded crossover PSO
FA	Firefly algorithm
GA	Genetic algorithm
HGA	Hybrid genetic algorithm
DE	Differential evaluation
MEFO	Modified electromagnetic field optimization
PSO	Particle swarm optimization
BBO	Biogeography based optimization
GWO	Grey wolf optimization
TLBO	Teaching learning based optimization
SA	Seeker algorithm
GSO	Group search optimization
AP	Analytic approach
BSA	Back tracking search algorithm
WOA	Whale optimization algorithm

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