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An Improved Optimal Solution for the Directional Overcurrent Relays Coordination Using Hybridized Whale Optimization Algorithm in Complex Power Systems

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ABSTRACT The directional overcurrent relays (DOCRs) coordination is a useful tool in guaranteeing the safe protection of the power system by the proper coordination of primary and backup protection systems. The optimization model of this problem is non-linear and highly constrained. The main objective of this paper is to develop a hybridized version of the Whale optimization algorithm referred to as HWOA for the optimal coordination of the DOCRs. The hybridization is done by deploying the simulated annealing (SA) in the WOA algorithm in order to improve the best solution found after each iteration and enhance the exploitation by searching the most promising regions located by the WOA algorithm, which leads toward a globally optimum solution. The proposed algorithm has been applied to five test systems, including the IEEE 3-bus, 8-bus, 9-bus, 15-bus, and 30-bus test systems. Furthermore, the results obtained using the proposed HWOA are compared with those obtained using the traditional WOA and a number of up-to-date algorithms. The obtained results show the effectiveness of the proposed HWOA in minimizing the relay operating time for the optimal coordination of the DOCRs.

INDEX TERMS Hybrid WOA, WOA, SA, directional overcurrent relay (DOCR), plug setting (PS), time dial setting (TDS), protection coordination.

I. INTRODUCTION

The electrical power system is a combination an electrical of the three sub systems that consists of generation, transmission and distribution system. Moreover the transmission system is responsible to transmit power from centralized plants to the customer. This transmission systems consist of conventional and non-conventional sources. The wind, geothermal, biomass and solar energy comes in the category of non- conventional sources that is mostly renewable energy sources. As a result of this non-conventional DGs in distribution systems causes a number of advantages as well as create some new obstacles for power system engineers. The mal-operation of the protection system is one of the key problem that power system engineer face. The protection of the distribution system might be assumed radial and unidirectional but after connecting DG, to the system, the system is no more radial and changed into loop system which result in mis-coordination and configuration of the protective relay [1]. In the beginning trial and error methods was used to obtain the setting of overcurrent relays (OCRs) [2], In [3], the setting of OCRs was find by using the topological methods in a multi-loop systems. In [4]– [7], different optimization techniques was deployed for solving the problem of coordination of relays. In [4]– [6], linear programming was used for finding the relay coordination in order to obtain the optimal time multiplier setting (TMS) for relays. In [7] the coordination was performed in meshed distribution system with user defined characteristic for DOCRs. Even though the attained result are deliberated the paramount

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alternative setting, but their solution depart from the optimal results. Recently, the researchers and scholar used different heuristic, metaheuristic and evolutionary algorithms for finding electrical engineering problem including the optimum setting of relays coordination [8]– [26]. In [8], the genetic algorithm (GA) was used for grounding grid simulation. In [9], [10], different version of JAYA algorithms was used for solving the economic load dispatch problem. In [11], the differential Evolution (DE) optimization was used to find the optimum TMS and pickup current (Ip) of the DOCRs In [12], the DOCRs problem was formulated as Mixed integer nonlinear programming (MINLP) and was solved using of DE. In [13], different version of DE was used to solve the optimum relay setting. In [14]–[17], various form of genetic algorithms (GA) were called to figure out the optimal DOCRs coordination problem. In [14], [15], the optimal setting and operational time of primary/secondary DOCRs were find with the help of designing a new problem formulation. In [16], a hybridized version of GA was used to find the optimum result of DOCRs setting. In [17], the optimum setting of DOCRs was resolved with the help of non-dominated sorting genetic algorithm (NSGA) for minimizing the discernment operational time of primary/secondary relays. In [18]–[20], to find the optimum DOCRs in interconnected power system a different feature of particle swarm optimizations (PSO) were used. In [21]–[22], the Root Tree Optimization (RTO) was recalled for finding the optimal values of OCRs. The main aim of the optimization of DOCRs is to minimize the total operating of the relays in order to reduce the power outages in the electrical power system as a result of single line to ground fault plus the operational time of the secondary relays. In [23], the grey wolf optimization was used to find the DOCRs coordination in the presence of distributed generators (DGs). The optimal coordination of DOCRs and optimal setting was done with the help of pattern search optimization (PS) in [24]. In [25], a non-standardized inverse time curves with Invasive Weed Optimization (IWO) was used to find an improved coordination of DOCRs. In order to find the precise DOCRs coordination an Electromagnetic Field Optimization (EFO) was used in [26]. Moreover this optimization methods obtain a better result than the hit and trial, topological and linear techniques, but these techniques are not adaptive and takes more computational time if any modifications occurs in the network.

Furthermore it has been realized that majority of this evolutionary optimization techniques suffer from serious drawbacks such as premature convergence, more computational time and the initial solution sensitivity. Also they differ widely in case of computational speed, storage requirement and implementation complexity. Heuristic algorithms, once in a while don't convey the ideal and global minima and do not converge to plausible result on the fact that there is no particular optimization exist that can accomplish the best result for a specific optimization issue [27].

This drawback can be overwhelmed by applying hybrid algorithms which consolidate both heuristic and conventional optimization algorithms. It has been reported in the literature that hybrid algorithms yield good and best results as contrasted with conventional or heuristic optimizations alone [28]. References [16], [28] engaged hybrid GAs by combining GA with LP and NLP. In these works, it was realized that hybrid GAs offered quicker merging and better result as contrasted with conventional GA. One such use of GA-LP is introduced in [29], wherein the DOCRs is tackled for an adaptive protection scheme conspire by gathering the DOCR settings dependent on system topological changes diminishing the quantity of coordination assessments. In [30], the authors have presented a hybrid heuristic technique called the GSA–SQP method to solve DOCR. The outcomes demonstrated that the GSA– SQP strategy gave better outcomes contrasted with IDE, GSA, and SQP. In [31] the DOCRs coordination was solved using the hybrid ACO-LP method, and it is discovered that the ACO-LP strategy brought better and ideal arrangements as contrasted with ACO alone.

SA [32] is a solitary procedure based metaheuristic technique, discovered by Kirkpatrick et al., and can be considered as a slope climbing based strategy that iteratively endeavor to improve an applicant solution with respect to the objective function. The improving move will be acknowledged, while the more regrettable move is acknowledged with a specific prospect to enable the calculation to escape from the nearby optima. The prospect of tolerating a more awful arrangement is controlled by the Boltzmann probability, $P = e^{-\theta/T}$, where θ is the distinction of the assessment of the target work between the best arrangement (Sol best) and the preliminary arrangement (Sol preliminary) and T is a parameter (called the temperature) that intermittently diminishes amid the search procedure as per some cooling timetable.

WOA [33], suggested by Mirjalili and Lewis, is a latest algorithm imitates the insightful searching conduct of the humpback whales. WOA has an extraordinary features less number of parameters to control, for example, since it incorporates just two primary inner parameters to be balanced, simple execution, and high adaptability. WOA calculation easily travel among the exploration and exploitation contingent upon just a single parameter. In the exploration stage the location of the search agents (solutions) are up- dated by a haphazardly chosen selected search agent instead of the best search agent find so far. Because of the effortlessness of WOA calculation in execution and the less reliance on parameters notwithstanding utilizing a logarithmic winding capacity which makes the algorithm cover the border area in the search space. The amazing properties of WOA and SA calculations can be consolidated to create a hybrid model to get preferred outcomes over utilizing every one independently. This hybridization is to enhance the exploitation property of the WOA algorithm.

This paper proposes a HWOA that is a combination of WOA and SA algorithms for obtaining the optimal values of TDS and PS in a DOCRs coordination problem in the power system, originally proposed by Mafarja et al. [34] for feature selection. The suggested approach aims to improve the exploitation of the WOA algorithm. To improve the exploitation, SA algorithm is employed in hybridization model; namely low-level teamwork hybrid (LTH). In LTH model, simulated annealing is used as a component in the WOA algorithm. It is used to search the neighbor- hood of the best search agent so far to insure that it's the local optima and to select search agents from the population because it gives the chance to all individuals to be selected.

II. DOCRS COORDINATION

In a reliable and healthy power system operations two condition must be fulfilled. In case of fault occur the DOCR should activate in its zone of protection. In the second condition the relay should not trip as a result of fault occur outside its zone of protection. Meanwhile if the primary relays protection fails than backup relay protection should take over the tripping activities within a certain interval of postponement know as coordination of secondary of protective relay. This protecting relays is the base for fulfilling the selective tripping by guaranteeing that the interval time of secondary relay is enough to consent primary relay to remove the fault. Also by connecting DGs to power distribution system it will affect the overcurrent protection operation as a result of bidirectional flow of fault current. Furthermore the magnitude of fault current varies depend on the DG size and location as a result a change in the operational period of relays occur which leads to mis-coordination of relays.

A. MATHEMATICAL MODELLING OF DOCR CHARACTERISTIC

The DOCR has an inverse time-current characteristic which can be delivered in a set of curves dependent on the value of the TDS. The relay operating time depends on the short-circuit current. It means that the operating time becomes longer as the fault current decreases. In general, the following equation represents the characteristic function of the overcurrent relay [19].

$$T = f(TDS, I, I_p) \tag{1}$$

where T is the relay operating time, I is the short-circuited current flowing through the relay and Ip is the pickup setting current. Accords to the IEC standard inverse type, Eq. (1) can be expressed as:

$$T_{op} = TDS_i\left(\frac{\alpha}{\left(\frac{I}{PS\times CTR}\right)^k - 1}\right) \tag{2}$$

B. PROBLEM FORMULATION

The DOCRs coordination problem is formulated as an optimization problem. The objective function is to minimize the sum of total operating of primary for a fault at the primary zone and could be illustrated as follow.

$$\min f = \sum_{i=1}^{n} T_{i,j} \tag{3}$$

where $T_{i,j}$ is the operational time of the primary relay for a fault at zone j.

C. DOCRs CONSTRAINTS

The operational time of secondary protection relay should be higher than that of the operational time of its primary protection and the CTI for the same fault type and location.

$$T_{bc} \geq T_{pr} + CTI \tag{4}$$

where T_{bc} and T_{pr} is operational time of the backup/primary relay. Moreover the objective function is subjected to another constraints depending on the limits of PS and TDS that are illustrated as follow.

$$TDS_i^{min} \leq TDS_i \leq TDS_i^{max} \tag{5}$$

$$PS_i^{min} \leq PS_i \leq PS_i^{max} \tag{6}$$

where TDS_i^{min} and TDS_i^{max} are lower and upper limits of TDS of the i^{th} relay. PS_i^{min} and PS_i^{max} are the lower and upper limits of PS of the i^{th} relay respectively.

III. WHALE OPTIMIZATION ALGORITHM

The WOA optimization algorithm is a new metaheuristic algorithm inspired by the foraging behavior of humpback whales. The humpback whales chase school of krill or little fishes near the surface by swimming around them inside a contracting circle and making particular rises along a circle or '9'- molded way (see Fig. 1). Encircling prey and spiral bubble-net attacking method were represented in the first phase of the algorithm; exploitation phase, the second phase where search randomly for a prey (exploration phase). The following subsections discuss the mathematical model of each phase in details. Note that in the equations, a uniform distribution will be used to generate random numbers.

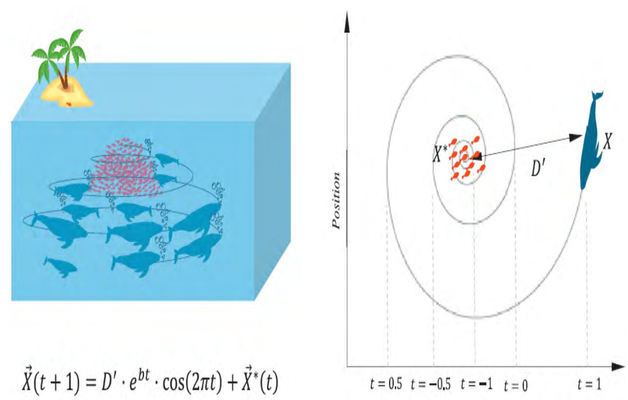

FIGURE 1. Unique bubble-net feeding methods of humpback whales and the mathematical model [34].

A. EXPLOITATION

To hunt a prey, humpback whales first encircle it. Eqs. (7) and (8) can be used to mathematically model this behavior

$$\vec{E} = \left|\vec{C}.\vec{Z}^*(t) - \vec{Z}(t)\right| \tag{7}$$

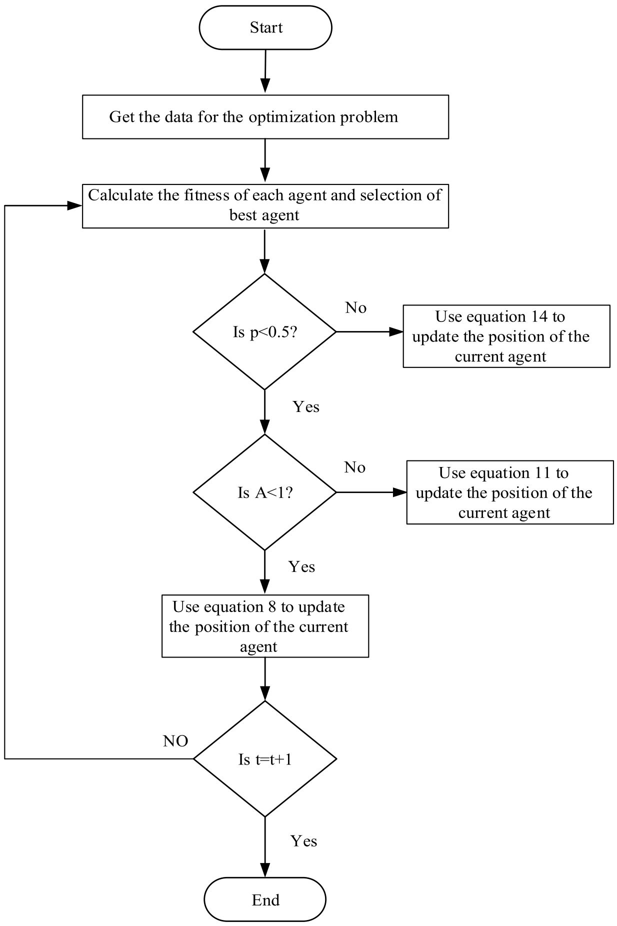

FIGURE 2. Flow chart of WOA.

$$\vec{Z}^{*}(t+1) = \vec{Z}^{*}_{(t)} - \vec{A}.D \tag{8}$$

where t is the current iteration, Z* denotes the provided best solution in the position vector Z; and A and C are the coefficient vectors. It should be noted that Z^* will be amended in each iteration and D determine the location of whale i to the pray.

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \tag{9}$$
$$\vec{C} = 2.\vec{r} \tag{10}$$

where 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. A decrease in the estimation of a from two to zero through the iterations of (8) results in this conduct. Likewise, by diminishing the value of a, which is a randomly chosen value in [−a, a], the change scope of 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 A in the interval [−1, 1].

$$\vec{Z}\,(t+1) = D^{'}.e^{bl}.\cos(2\pi l) + \vec{Z}^{*}(t) \tag{11}$$

where $D^{'}$ determines the location or distance of whale i to the prey and can be obtained as $D^{'} = \left|\vec{Z}^{*}(t) - \vec{Z}(t)\right|$ 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.

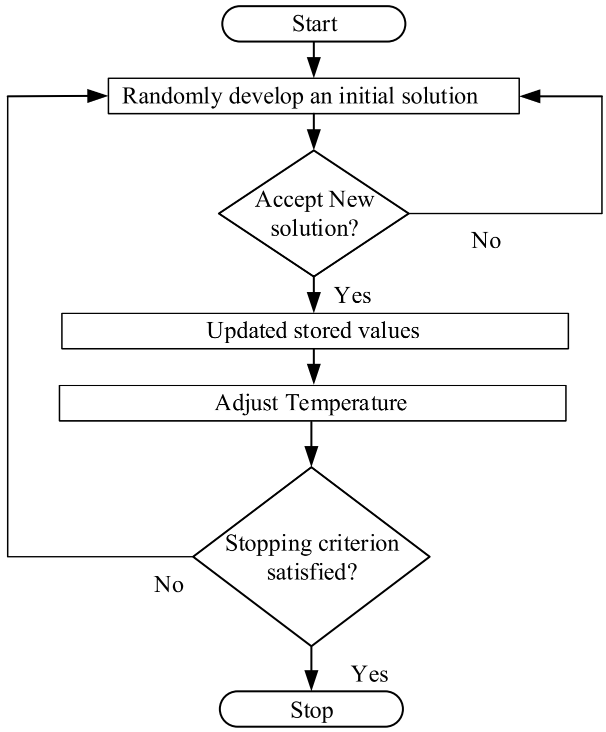

FIGURE 3. Flowchart of simulated annealing.

$$\vec{Z}(t+1) = \begin{cases} \vec{Z}(t) - \vec{A}.D & if\ p \leq 0.5 \\ \vec{D}^{'}.e^{bl}.\cos(2\pi l) + \vec{Z}^{*}(t) & if\ p \geq 0.5 \end{cases} \tag{12}$$

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

B. EXPLORATION PHASE

An equivalent technique dependent on the heterogeneity of the vector 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 be skilled in the behavior, where $|A| > 1$. 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:

$$\vec{D} = \vec{C}.\vec{Z}^{*}_{rand} - \vec{Z} \tag{13}$$
$$\vec{Z}\,(t+1) = \vec{Z}_{rand} - \vec{A}.\vec{D} \tag{14}$$

where $\vec{Z}_{rand}$ is an arbitrary position vector which is chosen from the existing population.

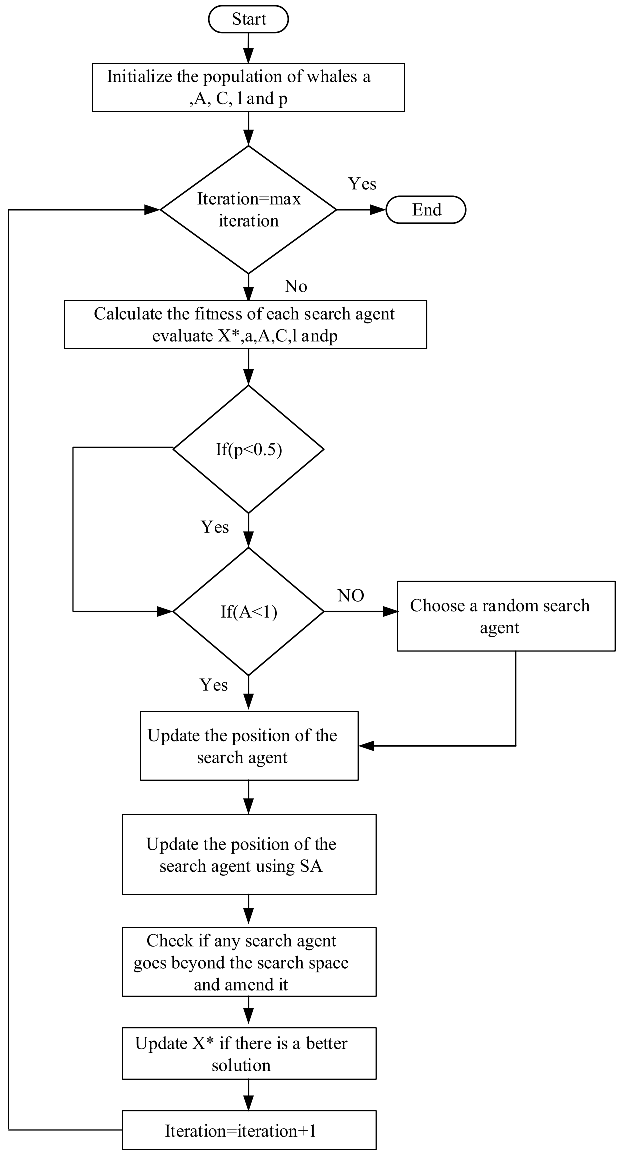

FIGURE 4. Flowchart of HWOA.

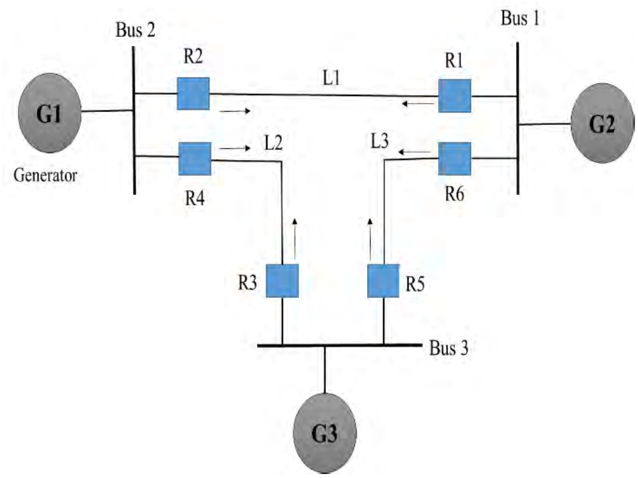

FIGURE 5. Test system 1.

TABLE 1. Short circuit test, test system 1.

Primary Relay	Fault Current (A)	Backup Relay	Fault Current (A)
1	1978.90	5	175.00
2	1525.70	4	545.00
3	1683.90	1	617.22
4	1815.40	6	466.17
5	1499.66	3	384.00
6	1766.30	2	145.34

TABLE 2. Tap setting and CT ratio, test system 1.

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

Figure 2 shows flowchart of WOA algorithm. It may be seen that WOA creates a random, initial population and evaluates it using a fitness function once the optimization process starts. After finding the best solution, the algorithm repeatedly executes the following steps until the satisfaction of an end criterion. Firstly, the main coefficients are updated. Secondly, a random value is generated. Based on this random value, the algorithm updates the position of a solution using either Eqs. (8) / (14) or Eq. (11). Thirdly, the solutions are prevented from going outside the search landscape. Finally, the algorithm returns the best solution obtained as an approximation of the global optimum. WOA is a population-based stochastic algorithm as mentioned above. What guarantees the convergence of this algorithm is the use of the best solution obtained so far to update the position of the rest of solutions. However, this mechanism might lead solutions to local optima. This is the reason of using random variables to switch between three equations to update the position of solutions. The balance between local optima avoidance (exploration) and convergence (exploitation) is done with the adaptive parameter a. This parameter smoothly reduces the magnitude of changes in the solutions and promotes convergence/exploitation proportional to the number of iterations.

IV. SIMULATED ANNEALING

SA is a solitary procedure based metaheuristic technique, discovered by Kirkpatrick et al., and can be considered as a slope climbing based strategy that iteratively endeavor to improve an applicant solution with respect to the objective function. The improving move will be acknowledged, while the more regrettable move is acknowledged with a specific prospect to enable the calculation to escape from the nearby

TABLE 3. Optimal TDS and PS for, test system 1.

Relay No	WOA		HWOA	
	TDS	PS	TDS	PS
1	0.0500	1.2500	0.0500	1.2500
2	0.0500	1.2500	0.0500	1.2500
3	0.05553	1.3837	0.0500	1.2500
4	0.0500	1.2500	0.0500	1.2500
5	0.0710	2.4746	0.0612	1.7557
6	0.1587	2.2163	0.8065	1.2500
T_{op}(s)	1.5262		1.5029	

TABLE 4. Comparison of the HWOA result with WOA and with literature for test system 1.

Method	Objective Function
TLBO (MOF) [36]	6.972
TLBO [36]	5.3349
MDE [37]	4.7806
SM [4]	1.9258
MINLP [38]	1.727
SA [38]	1.599
MPSO [39]	1.9258
BB0-LP [40]	1.59871
WOA	1.5262
HWOA	1.5029

TABLE 5. Comparison of total net gain in time obtained by HWOA with the algorithms used in the literature.

Net gain	$\sum \Delta$(t) s
HWOA/ TLBO (MOF)	5.4691
HWOA/ TLBO	3.832
HWOA/MDE	3.277
HWOA/SM	0.4229
HWOA/MINLP	0.2198
HWOA/SA	0.0961
HWOA/PSO	0.4229
HWOA/BBO-LP	0.09581
HWOA/WOA	0.0233

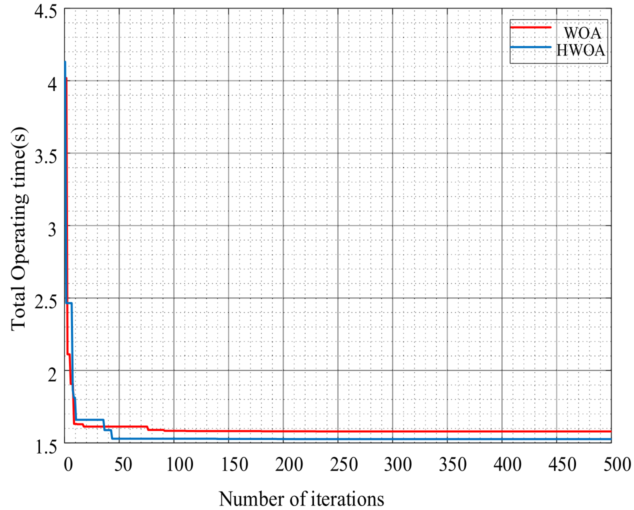

FIGURE 6. Convergence characteristic of HWOA vs WOA for Test System1.

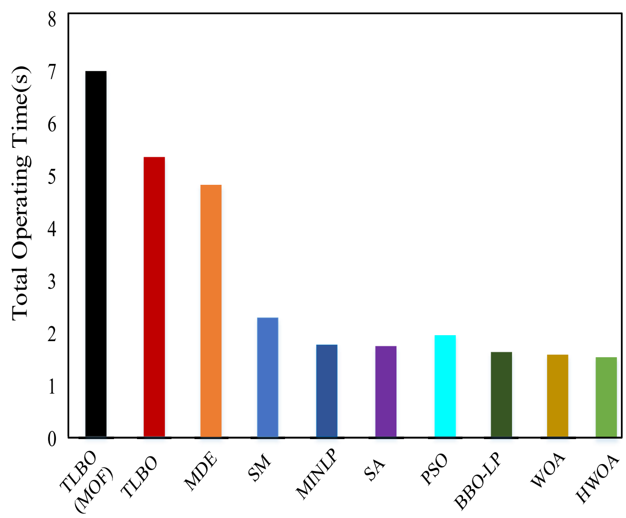

FIGURE 7. Graphical illustration of optimized total operating time of the proposed HWOA compared to the literature for test system 1.

optima. The prospect of tolerating a more awful arrangement is controlled by the Boltzmann probability, P = e $-\theta/$ T, where θ is the distinction of the assessment of the target work between the best arrangement (Sol best) and the preliminary arrangement (Sol preliminary) and T is a parameter (called the temperature) that intermittently diminishes amid the search procedure as per some cooling timetable. In this work, the initial temperature is set to $2* |N|$, where $|N|$ represents the number of attributes for each dataset, and the cooling schedule is calculated as $T = 0.93*T$. Figure 3 shows the flowchart of SA algorithm.

V. HYBRIDIZED WHALE OPTIMIZATION ALGORITHM

This methodology signifies a hybridization between global search (WOA) and local search algorithm (SA). Since, in the WOA algorithm, exploitation (as in Eqs. (8) and (11)) relies on scheming the distance between the search agent and the finest known whale. We consider that using a competent local search algorithm to find the locality around the finest known solution will enhance the results. Moreover, since the examination in the native WOA algorithm (as in Eq. (14)) relies on varying the position of each search agent corresponding to a randomly preferred solution that gives further chance to the fragile solutions to be prefers during the search process dependent on the selection heaviness which advances the diversification competence of WOA algorithm. The WOA algorithm utilizes a blind operator to perform the part of exploitation irrespective of the fitness value of the existing solution and the operated one. We substituted this operator with a local search which examine a solution as its initial state, work on it, and substitute the original solution by the improved one. This methodology signifies a hybridization

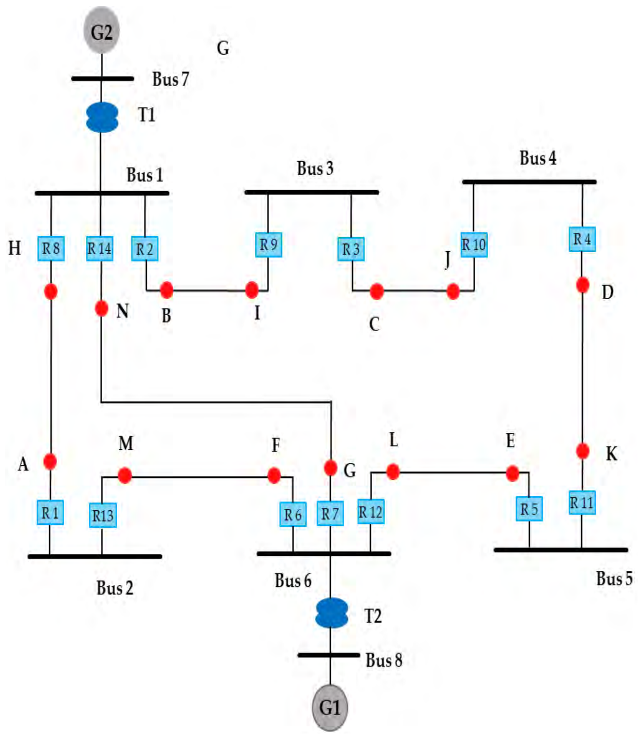

FIGURE 8. Test system 2.

TABLE 6. Current transformer ratio for test system 2.

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

between global search (WOA) and local search algorithm (SA). In the proposed methodology, hybridization model between the two algorithms are considered. SA algorithm is embedded in WOA algorithm to find for the finest solution in the neighbor of both the randomly preferred solution (to replace Eq. (14)) and the neighbor of the finest known solution (to substitute Eq. (8)) and substitute the original one. This approach is called HWOA. This process enhances the exploitation capacity of WOA algorithm. SA algorithm in this methodology works as an operator in WOA algorithm. In HWOA, WOA uses random selection system to select the random solution that permits the algorithm to examine

TABLE 7. Short circuit test for test system 2.

Primary Relay	Fault Current (A)	Backup Relay	Fault Current (A)
1	3232	6	3232
2	5924	1	996
2	5924	7	1890
3	3556	2	3556
4	3783	3	2244
5	2401	4	2401
6	6109	5	1197
6	6109	14	1874
7	5223	5	1197
7	5223	13	987
8	6093	7	1890
8	6093	9	1165
9	2484	10	2484
10	3883	11	2344
11	3707	12	3707
12	5899	13	987
12	5899	14	1874
13	2991	8	2991
14	5199	1	996
14	5199	9	1165

TABLE 8. Optimal TDS and PS of 8-bus system.

Relay No	WOA		HWOA	
	TDS	PS	TDS	PS
1	0.1000	1.2500	0.1000	1.2500
2	0.5929	1.3746	0.5381	1.2500
3	0.1007	1.2586	0.1000	1.2500
4	0.1000	1.2500	0.2164	1.2500
5	0.3581	2.0638	0.1000	1.2500
6	0.2490	1.5745	0.2689	1.2500
7	0.1018	1.2726	0.1000	1.2500
8	0.3430	1.8559	1.1000	1.2500
9	0.1000	1.2500	0.1000	1.2500
10	0.1000	1.2500	0.1000	1.2500
11	0.1004	1.2548	0.1000	1.2500
12	0.1521	1.901	0.1000	1.2500
13	0.1000	1.2500	0.1000	1.2500
14	0.1000	1.2500	0.1000	1.2500
T_{op}(s)	5.9535		5.8568	

the feature space. Figure 4 shows the flowchart of HWOA algorithm.

VI. RESULTS AND DISCUSSION

In this section the proposed HWOA based for optimal coordination of DOCRs has been successfully implemented on IEEE 3-bus, 8-bus, 9-bus, 15-bus and 30-bus system. The results have been obtained by developing an accurate simulation program using MATLAB software *@R2018b*.

A. TEST SYSTEM 1: THE 3-BUS SYSTEM

The first system investigated in this paper is the 3-bus test system shown in Fig. 5. It is composed of 3 buses, 3 generators,

TABLE 9. Comparison of the HWOA with methods used in the literature for Test system 2.

Method	Objective Function
SA [38]	8.4270
GA [28]	11.001
HGA-LP [28]	10.9499
NLP[41]	6.41169
LM [41]	11.0645
BBO-LP [40]	8.75559
MILP[42]	8.0061
FA [43]	6.6463
MEFO [26]	6.349
WOA	5.9535
HWOA	5.8568

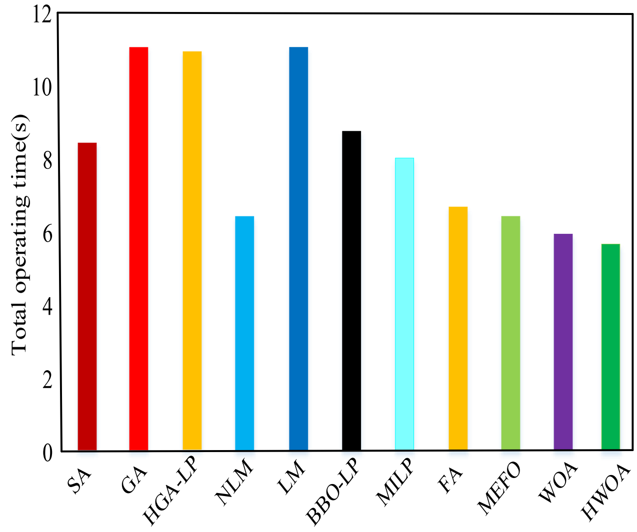

FIGURE 10. Graphical illustration of optimized total operating time of the HWOA with the literature for test system 2.

TABLE 10. Comparison of total net gain in time obtained by HWOA with the algorithms used in the literature.

Net gain	$\sum \Delta(t)$ s
HWOA/ SA	2.5702
HWOA/ GA	5.1442
HWOA/HGA-LP	5.0931
HWOA/NLP	0.55489
HWOA/LP	5.2077
HWOA/BBO-LP	2.89879
HWOA/FA	0.7895
HWOA/MEFO	0.4922
HWOA/WOA	0.0967

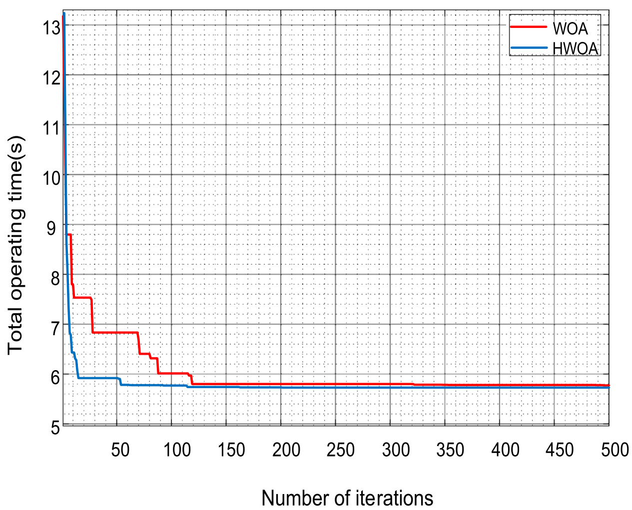

FIGURE 9. Convergence characteristic of HWOA vs WOA for test system 2.

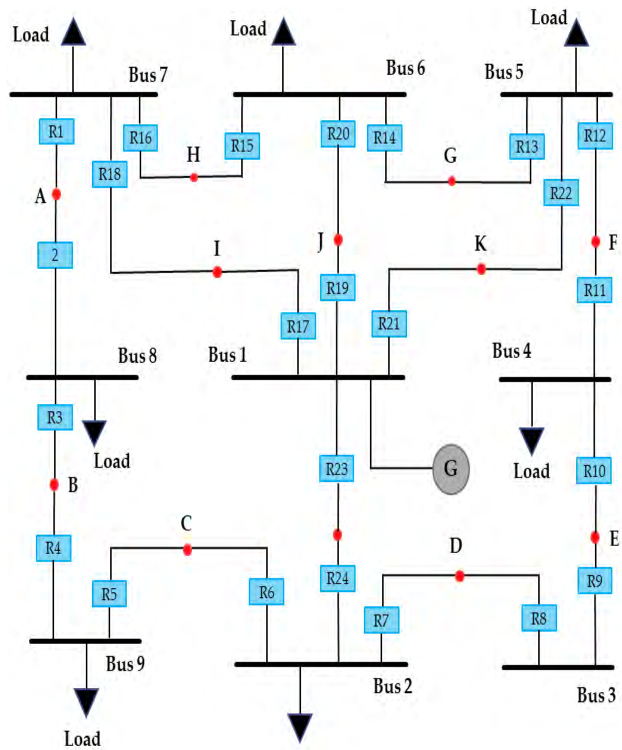

FIGURE 11. Test System 3.

3 lines and 6 relays. The short-circuit currents measured by primary and backup relays are given in Table 1. The Data of this test case could be found in [38]. The value of CT ratio and related tap setting is given in Table 2. The lower and upper values of TDS are set 0.05 and 1.1, respectively, while those of PS are set 1.25 and 5.0, respectively. The CTI value is selected as 0.3s. The optimal TDS and PS values achieved by the proposed algorithm are tabulated in Table 3. Table 4 shows the relative result of the proposed algorithm in comparison to other published techniques reported in the literature. It was observed that the suggested HWOA accomplishes a better result as compared to other methods. The overall net gain in time obtained by the suggested HWOA is depicted in Table 5, which shows the superiority of the HWOA over other methods explained in the literature. Fig. 6 depicts the HWOA convergence characteristic obtained during the course of the simulation. Fig. 7 provides the graphical illustration of

TABLE 11. Short circuit test for test system 3.

Primary Relay	Fault Current (A)	Backup Relay	Fault Current (A)
1	4863.6	15	1168.3
1	4863.6	17	1293.9
2	1634.4	4	1044.2
3	2811.4	1	1361.6
4	2610.5	6	1226
5	1778	3	1124.4
6	4378.5	8	711.2
6	4378.5	23	1345.5
7	4378.5	5	711.2
7	4378.5	23	1345.5
8	1778	10	1124.4
9	2610.5	7	1226
10	2811.4	12	787.2
11	1634.4	9	1044.2
12	2811.4	14	1168.3
12	2811.4	21	1293.9
13	3684.5	11	653.6
13	3684.5	21	1293.9
14	4172.5	16	1031.7
14	4172.5	19	1264.1
15	4172.5	13	1031.7
15	4172.5	19	1264.1
16	3684.5	2	653.6
16	3684.5	17	1293.9
17	7611.2	-	0
18	2271.7	2	653.6
18	2271.7	15	1168.3
19	7435.8	-	0
20	2624.2	13	1031.7
20	2624.2	16	1031.7
21	7611.2	-	0
22	2271.7	11	653.6
22	2271.7	14	1168.3
23	7914.7	-	0
24	1665.5	5	711.2
24	1665.5	8	711.2

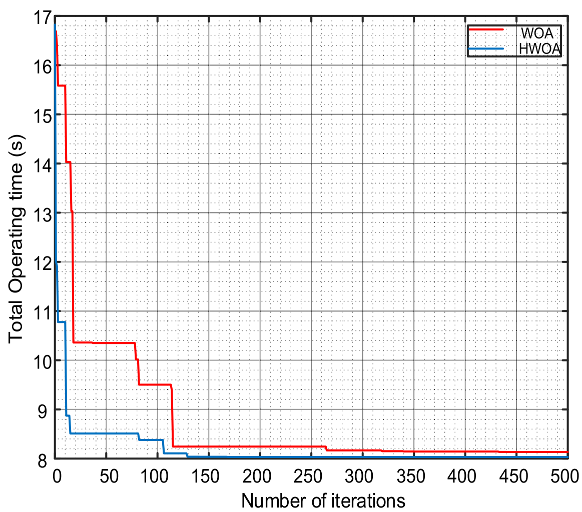

FIGURE 12. Convergence characteristic of HWOA vs WOA for test system 3.

the optimized minimum total operating time achieved by the suggested HWOA as compared with other techniques in the literature.

TABLE 12. Optimal TDS and PS for test system 3.

Relay No	WOA		HWOA	
	TDS	PS	TDS	PS
1	0.2316	2.4466	0.1000	1.5000
2	0.1001	1.5014	0.1000	1.5000
3	0.2377	2.4650	0.1000	2.5000
4	1.200	2.5000	1.0000	2.3963
5	0.1469	2.2553	0.1000	2.5000
6	0.7059	2.5000	0.1000	1.5000
7	0.1761	2.4542	0.2053	2.3111
8	0.5674	2.4224	0.1000	1.5000
9	1.2000	2.5000	1.0601	1.5000
10	0.2193	2.3922	0.1000	2.4680
11	0.6990	1.8076	0.1000	1.5000
12	0.1368	1.8399	0.1000	1.7977
13	0.1454	2.1276	0.1395	1.5000
14	0.1497	2.5000	0.1000	1.5000
15	0.1632	2.0901	0.1000	1.5000
16	1.1431	2.3815	1.1000	2.0797
17	0.2636	1.6991	0.4011	1.5000
18	0.14875	2.2135	0.1000	1.5000
19	0.12251	1.8376	0.1000	1.5000
20	0.18656	2.4963	1.0000	1.5000
21	0.51479	1.5402	0.1511	1.5000
22	0.17653	2.5000	0.2196	1.5000
23	1.2000	2.5000	1.0152	1.5000
24	0.1303	1.9311	0.1000	1.5000
$T_{op}(s)$	8.3849		8.1968	

TABLE 13. Comparison of the HWOA with methods used in the literature for test system 3.

Method	Objective Function
TLBO [44]	82.9012
IDE [44]	59.6471
MTALBO [44]	41.9041
GA [16]	32.6058
BBO [38]	28.8348
BH [26]	25.884
NPL[28]	19.4041
PSO [45]	13.9742
HS [26]	9.838
DE [45]	8.6822
WOA	8.3849
HWOA	8.1968

TABLE 14. Comparison of total net gain in time obtained by HWOA with the algorithms used in the literature.

Net gain	$\sum \Delta(t)$ s
HWOA/ TLBO	74.7044
HWOA/ IDE	51.4503
HWOA/MTALBO	33.7073
HWOA/GA	24.409
HWOA/BBO	20.638
HWOA/BH	17.6872
HWOA/NPL	11.2073
HWOA/PSO	5.7774
HWOA/HS	1.6412
HWOA/DE	0.4854
HWOA/WOA	0.1881

B. TEST SYSTEM 2: THE 8-BUS SYSTEM

The second system investigated in this paper is the 8-bus test sys-tem shown in Fig. 8. It is composed of 8 buses,

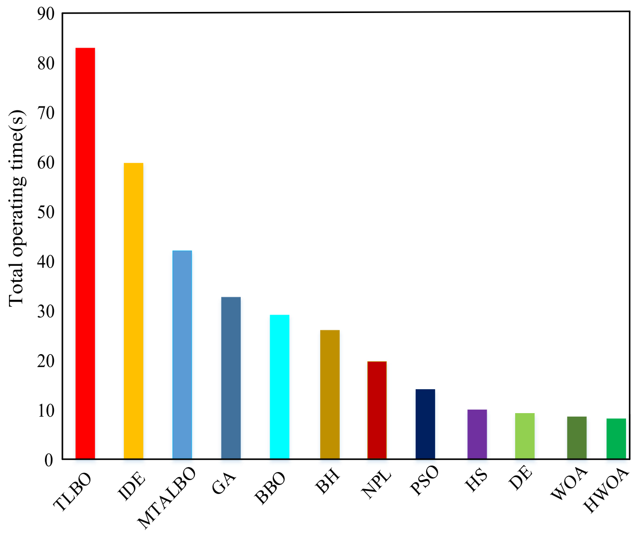

FIGURE 13. Graphical representation of optimized total operating time of the HWOA with the literature for test system 3.

2 generators, 2 transformers, 7 lines and 14 relays. The main characteristics of this system are given in Table 6. The short-circuit currents measured by primary and backup relays are given in Table 7. Moreover, the lower and upper values corresponding to the lower and upper bounds of TDS are set 0.1 and 1.2, respectively, while those of PS are set 1.25 and 2.5, respectively. The optimal TDS and PS for DOCRs obtained by the suggested HWOA are shown in Table 8, while Table 9 depicts the relative comparison of the suggested HWOA with WOA and other published techniques explained in the literature. As shown in Table 9, the suggested HWOA has obtained an improved result for the above stated IEEE 8-bus system. The assessment of total net gain in time obtained in this case by the suggested HWOA is shown in Table 10 with respect to other evolutionary algorithms mentioned in the literature. It was observed that the HWOA algorithm has an advantage of net gain in time over other techniques and shows satisfactory and improved results.

TABLE 15. Current transformer ratio.

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

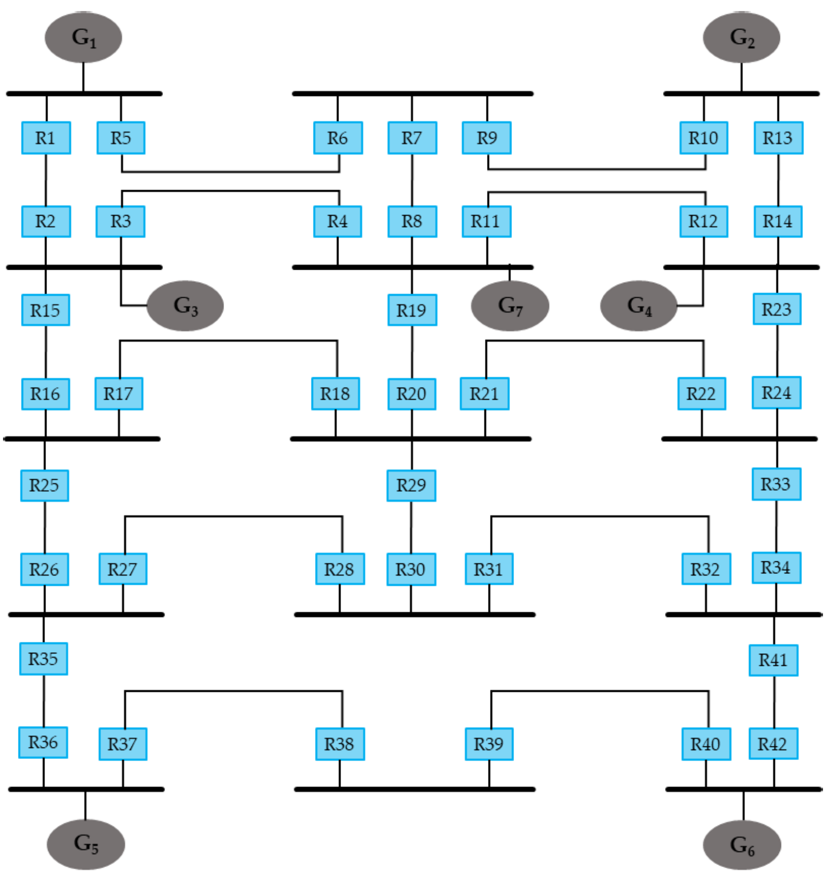

FIGURE 14. Test system 4.

TABLE 16. Short circuit test for test system 4.

Primary Relay	Fault Current (A)	Backup Relay	Fault Current (A)	Primary Relay	Fault Current (A)	Backup Relay	Fault Current (A)
1	3621	6	1233	20	7662	30	681
2	4597	4	1477	21	8384	17	599
2	4597	16	743	21	8384	19	1372
3	3984	1	853	21	8384	30	681
3	3984	16	743	22	1950	23	979
4	4382	7	1111	22	1950	34	970
4	4382	12	1463	23	4910	11	1475
4	4382	20	1808	23	4910	13	1053
5	3319	2	922	24	2296	21	175
6	2647	8	1548	24	2296	34	970
6	2647	10	1100	25	2289	15	969
7	2497	5	1397	25	2289	18	1320
7	2497	10	1100	26	2300	28	1192
8	4695	3	1424	26	2300	36	1109
8	4695	12	1463	27	2011	25	903
8	4695	20	1808	27	2011	36	1109
9	2943	5	1397	28	2525	29	1828
9	2943	8	1548	28	2525	32	697
10	3568	14	1175	29	8346	17	599
11	4342	3	1424	29	8346	19	1372
11	4342	7	1111	29	8346	22	642
11	4342	20	1808	30	1736	27	1039
12	4195	13	1503	30	1736	32	697
12	4195	24	753	31	2867	27	697
13	3402	9	1009	31	2867	29	1828
14	4606	11	1475	32	2069	33	1162
14	4606	24	753	32	2069	42	907
15	4712	1	853	33	2305	21	1326
15	4712	4	1477	33	2305	23	979
16	2225	18	1320	34	1715	31	809
16	2225	26	905	34	1715	42	907
17	1875	15	969	35	2095	25	903
17	1875	26	905	35	2095	28	1192
18	8426	19	1372	36	3283	38	882
18	8426	22	642	37	3301	35	910
18	8426	30	681	38	1403	40	1403
19	3998	3	1424	39	1434	37	1434
19	3998	7	1111	40	3140	41	745
19	3998	12	1463	41	1971	31	809
20	7662	17	599	41	1971	33	1162
20	7662	22	642	42	3295	39	896

Fig. 9 depicts the convergence characteristic of the HWOA vs WOA achieved during the course of the simulation. Fig. 10 provides the graphical illustration of the optimized minimum total operating time achieved by the proposed HWOA in comparison to the literature.

C. TEST SYSTEM 3: THE 9- BUS SYSTEM

The 3rd system presented in this paper is IEEE 9- bus system that is composed of 9 buses and 12 lines and is powered by a generator associated with bus 1 as shown in figure 11. The short circuit test for primary and back up relays are shown in table 11. The proposed setting value for current transformer ratio is set 500/1 for all relays. The lower and upper values for TDS and PS are set to 0.1 to 1.2 and 1.5 to 2.5 respectively. A coordination interval is consider 0.2s. The optimum values for TDS and PS of the DOCRs obtained by WOA are shown in Table 12. Table 13 depicts the relative result of the suggested HWOA with other published

TABLE 17. Optimal TDS and PS for test system 4.

Relay No	WOA		HWOA		Relay No	WOA		HWOA	
	TDS	PS	TDS	PS		TDS	PS	TDS	PS
1	0.1000	0.5000	0.10000	0.500000	22	0.1039	0.5195	0.10000	0.500000
2	0.1030	0.5150	0.10000	0.500000	23	0.1010	0.5049	0.10000	0.500000
3	0.1078	0.5393	0.10000	0.500000	24	0.1000	0.5000	0.10000	0.500000
4	0.1000	0.5000	0.10000	0.500000	25	0.1139	0.5695	0.10000	0.500000
5	0.1041	0.5206	0.10000	0.500000	26	0.1101	0.5504	0.10000	0.500000
6	0.1240	0.6201	0.10000	0.500000	27	1.0414	2.3668	0.18015	0.500000
7	0.1000	0.5003	0.10000	0.500000	28	0.3260	1.1297	0.95357	0.944212
8	0.1000	0.5000	0.10000	0.500000	29	0.2249	0.7461	1.00732	1.007835
9	0.1455	0.7275	0.10000	0.500000	30	0.1000	0.5000	0.1000	0.500000
10	0.1078	0.5392	0.10000	0.500000	31	0.1483	0.5000	1.00055	1.001039
11	0.1020	0.5103	0.10000	0.500000	32	0.1056	0.5280	0.97867	0.981550
12	0.1000	0.5000	0.10000	0.500000	33	0.1487	0.7438	0.10000	0.50000
13	0.1070	0.5350	0.10000	0.500000	34	0.2123	0.5689	1.0000	0.99999
14	1.1000	2.5000	0.10000	0.500000	35	0.1152	0.5759	0.10000	0.500000
15	0.1000	0.5000	0.10000	0.500000	36	0.7140	1.6790	0.25093	0.500000
16	0.1148	0.5742	0.10000	0.500000	37	0.1245	0.6229	0.10000	0.500000
17	0.1015	0.5077	0.10000	0.500000	38	0.1066	1.1121	1.1000	1.493574
18	0.4930	1.4766	1.00021	1.000214	39	0.4113	0.9377	0.10000	0.500000
19	0.1539	0.7699	0.16858	0.538100	40	0.1515	0.7576	0.10000	0.500000
20	0.2644	0.9671	0.90107	1.500000	41	0.4033	0.9166	1.10000	2.500000
21	0.1557	0.7785	0.99984	0.999394	42	0.1105	0.5195	0.10000	0.500000
T_{op}(s)	11.2670		9.5559						

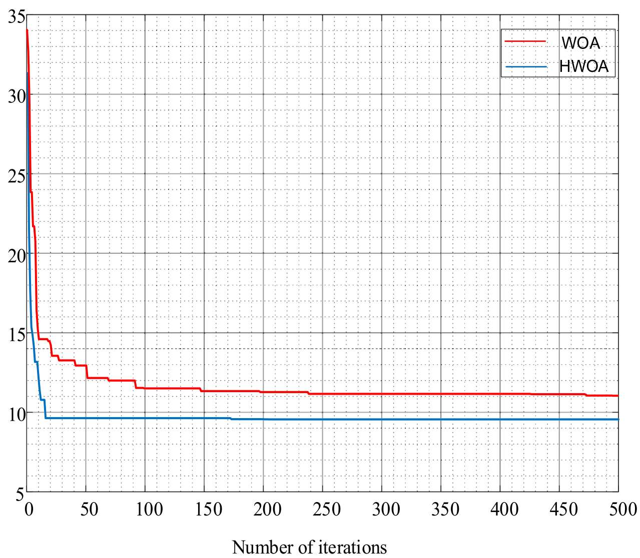

FIGURE 15. Convergence characteristic of HWOA vs WOA for test system 4.

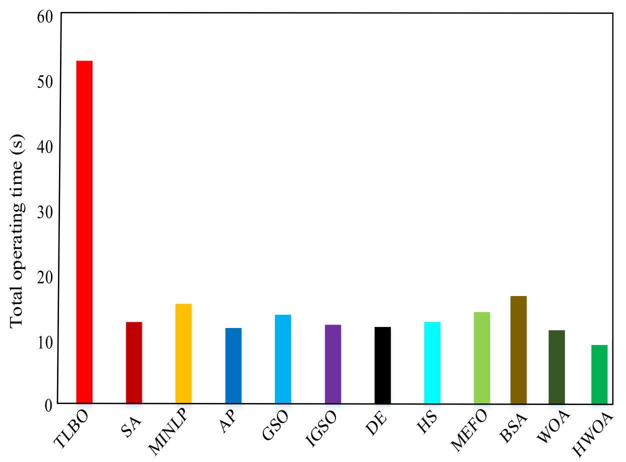

FIGURE 16. Graphical representation of optimized total operating time of the HWOA compared with the literature for test system 4.

TABLE 18. Comparison of the HWOA with methods used in the literature for test system 4.

Net gain	$\sum \Delta(t)$ s
TLBO[44]	52.5039
SA[38]	12.227
MINPL[38]	15.335
AP[46]	11.6542
GSO[47]	13.6542
IGSO[47]	12.135
DE[45]	11.7591
HS [45]	12.6225
MEFO[26]	13.953
BSA[48]	16.293
WOA	11.2670
HWOA	9.5559

algorithms cited in the literature. As indicated by Table 13, the suggested HWOA 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 HWOA is shown in Table 14. It is seen that the HWOA algorithm has promising advantages of net gain in time over other algorithms. Fig. 12 delineates the convergence characteristic of HWOA vs WOA obtained during the simulation. Fig. 13 provides a graphical illustration of the optimized minimum total operating time achieved by the proposed algorithm compared with different algorithms referenced in the literature.

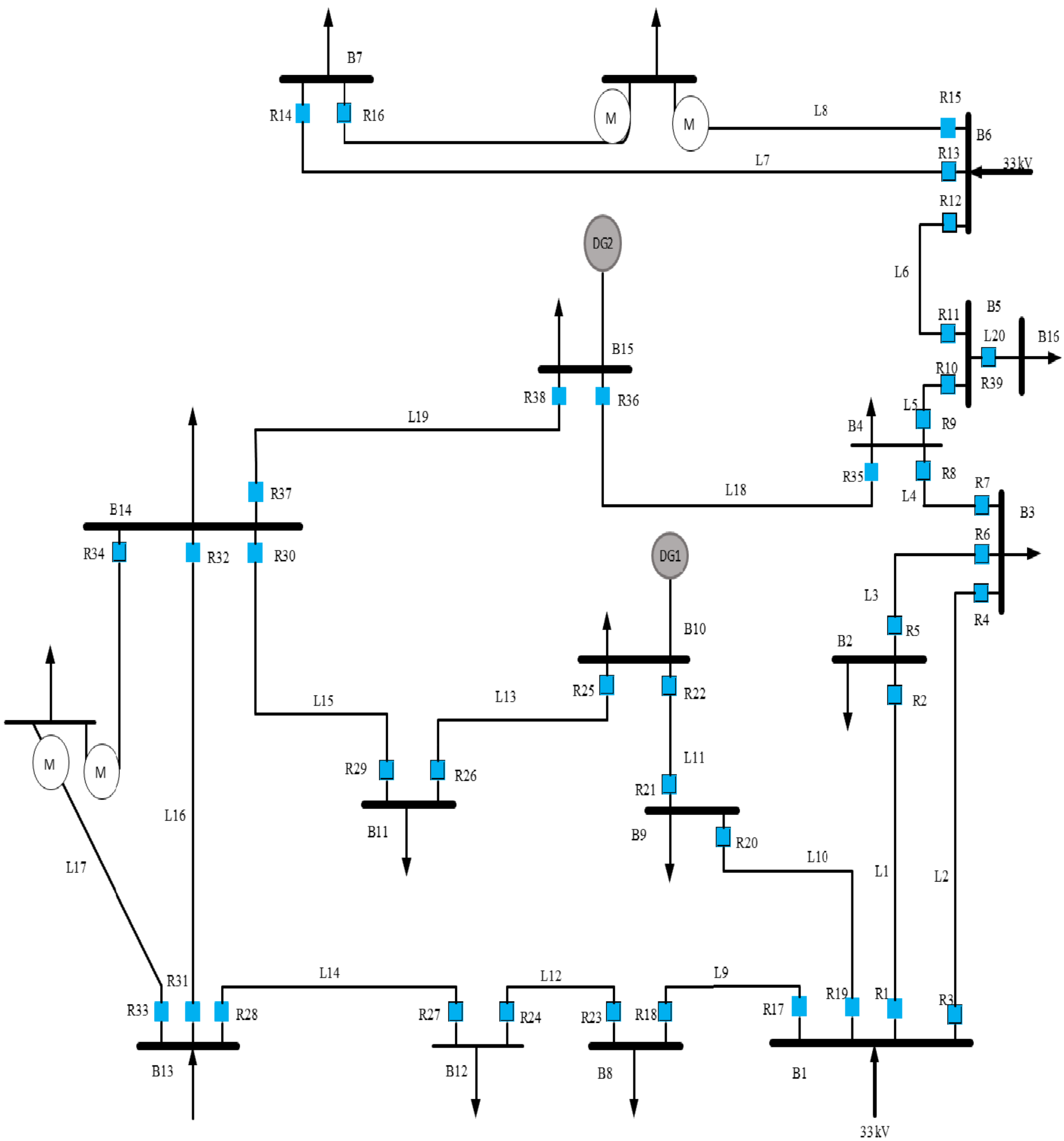

FIGURE 17. Diagram of test system 4.

D. TEST SYSTEM 4: THE 15- BUS SYSTEM

This system is a highly penetrated distribution network with several distributed generation (DG) units. The system has 15 buses, 21 lines, and 42 relays as shown in Fig. 14. The proposed setting for current transformer ratios and primary/backup relationships for the relays is shown in Table 15. The short circuit cur-rents measured by primary and backup relays are given in Table 16. 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 17, while Table 18 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 Fig. 15, which indicates that the convergence is quicker and yields an improved value for the objective function in fewer iterations. The graphical representation of the total operating time yielded by the suggested HWOA vs WOA is shown in Fig. 16 with other published

TABLE 19. Comparison of total net gain in time obtained by HWOA with the algorithms used in the literature.

Net gain	∑ Δ(t) s
HWOA/ TLBO	41.29449
HWOA/ SA	2.6711
HWOA/MINPL	5.7791
HWOA/AP	2.0952
HWOA/GSO	4.0983
HWOA/IGSO	3.1791
HWOA/DE	2.2032
HWOA/HS	3.0666
HWOA/MEFO	4.3971
HWOA/BSA	6.7371
HWOA/WOA	1.7111

techniques, which indicate the optimized values of total operating time. The advantage in overall net gain in time obtained by the suggested HWOA is presented in Table 19, showing the dominance of the HWOA algorithm over recent published methods.

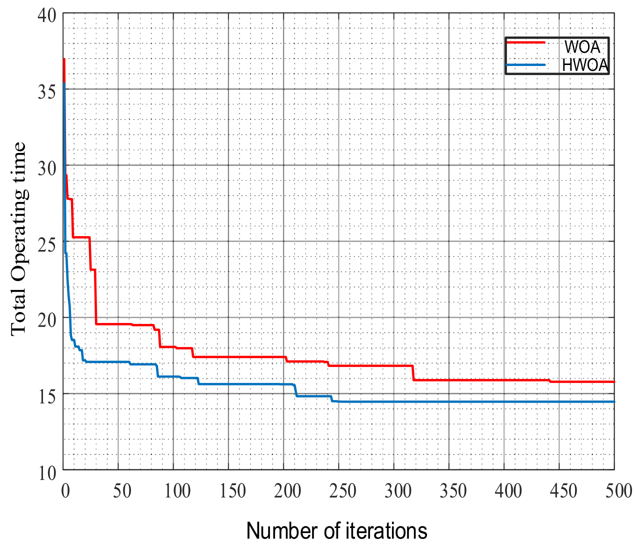

FIGURE 18. Convergence characteristic of HWOA vs WOA for test system 5.

E. TEST SYSTEM 5: THE 30-BUS SYSTEM

Fig. 17 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

TABLE 20. Three phase short circuit test for test system 5.

Primary Relay	Fault Current (A)	Backup Relay	Fault Current (A)	Primary Relay	Fault Current (A)	Backup Relay	Fault Current (A)
3	4086.7	1	4086.7	9	7212.6	20	1103.5
4	5411.2	2	2138.8	10	7339.3	20	1095.8
22	4333.0	2	2147.0	1	7665.3	21	698.8
4	5411.2	3	5411.2	9	7212.6	21	721.2
21	5411.8	3	5411.8	10	7339.6	21	716.1
5	4960.8	4	4960.8	20	3481.5	22	3481.5
18	4719.4	4	4719.4	21	5411.8	23	2193.5
6	2416.0	5	2416.0	22	4333.0	23	2204.6
7	5669.0	6	5669.0	18	4719.4	24	1717.7
8	5607.7	6	5607.7	23	3689.7	24	1724.2
27	1472.3	7	1472.3	24	2695.0	25	2695.0
26	1026.8	8	1026.8	1	7665.3	28	1552.0
12	5034.9	9	5034.9	2	7985.7	28	1545.8
11	3457.1	10	3457.1	10	7339.3	28	1538.0
13	3227.3	11	3727.3	1	7665.3	29	1380.6
14	2906.5	12	2906.5	2	7985.7	29	1375.2
15	2660.5	13	2660.5	9	7212.6	29	1379.0
16	6185.6	14	6185.6	29	2518.9	30	2518.9
17	7492.9	14	7492.9	28	2036.8	31	2036.8
19	5445.2	15	5445.2	30	2998.8	32	2149.0
35	4222.0	15	4222.0	31	3263.6	33	3263.6
36	6420.2	15	6420.2	32	2930.4	34	2930.4
19	5445.2	16	5445.2	17	7492.9	35	1885.4
34	5796.6	16	5796.6	33	6456.2	35	1885.4
36	6420.2	16	6420.2	16	6185.6	36	490.9
19	5445.2	17	5445.2	33	6456.2	36	500.6
34	5796.6	17	5796.6	5	4960.8	37	1961.0
35	4222.0	17	4222.0	23	3689.7	37	1968.5
38	3133.2	18	3133.2	34	5796.6	38	1886.8
37	3788.9	19	3788.9	35	4222.0	38	1896.7
2	7985.7	20	7985.7	36	6420.2	38	1867.7

TABLE 21. Optimal TDS and PS for test system 5.

Relay No	WOA		HWOA	
	TDS	PS	TDS	PS
1	0.1131	1.6958	0.1042	1.5000
2	0.1000	1.5000	0.1000	1.5000
3	0.1007	1.5109	0.1551	1.5000
4	0.1007	1.5111	0.1000	1.5000
5	0.1000	1.5000	0.1000	1.5000
6	0.9236	2.4761	0.4495	1.5000
7	0.1000	1.5005	0.1000	1.5000
8	0.1000	1.5000	0.1000	1.5000
9	0.1001	1.5029	0.1000	1.5000
10	0.1002	1.5042	0.1000	1.5000
11	0.1076	1.6149	0.1000	1.5000
12	0.1000	1.5000	0.1333	1.5000
13	0.1074	1.6118	0.1284	1.5000
14	1.0933	2.4849	0.1000	1.5000
15	0.6461	2.3447	1.0985	1.5000
16	0.8541	1.9412	0.1000	1.5000
17	0.2737	1.7453	1.1000	2.3686
18	0.6984	2.1623	0.1000	1.5000
19	0.1046	1.5824	0.1000	1.5000
20	0.2328	2.4762	1.1000	2.1106
21	0.1672	2.3334	1.1000	1.5000
22	0.1118	1.6782	0.1000	1.5000
23	0.1003	1.5000	0.1000	1.5000
24	0.1000	1.5000	0.1000	1.5000
25	0.1013	1.5205	1.0006	1.5000
26	0.1757	2.3145	0.1145	1.5000
27	0.1037	1.5555	0.9998	1.5000
28	0.2170	2.3228	0.9997	1.5000
29	0.1990	2.1887	0.9813	1.5000
30	0.2856	2.5000	0.1926	1.5000
31	0.3598	2.0241	1.0369	1.5000
32	0.1049	1.5747	0.1000	1.5000
33	0.1522	2.1039	1.1000	1.5000
34	0.1000	1.5006	0.7943	1.5000
35	0.2242	2.4661	1.1000	1.5000
36	0.1271	1.9075	0.1000	1.5000
37	0.1727	2.4772	0.1000	1.5000
38	0.2007	1.7111	1.0024	1.5000
39	0.1002	1.5035	0.9255	1.5000
T_{op}(s)	15.7139		14.4646	

and information of the network is presented in [35]. The framework has 20 lines (L1, L2, …, L20) and is protected by 39 DOCRs (R1, R2,…, R39) having 64 essential reinforcement assortments amongst them. The fault current going through the primary/backup OCRs for different close-end three-phase faults is specified in Table 20. 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 1-4, 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 (less than two times of the maximum load current of the relay) resulting in a greater working time of the backup OCRs; subsequently, the minimum CTI requirements are always maintained for these combinations.

TABLE 22. Comparison of the HWOA with methods used in the literature for test system 5.

Method	Objective Function
GA[45]	28.0195
PSO [45]	39.1836
DE [45]	17.8122
HS[45]	19.2133
SOA[45]	33.7734
AIS[49]	14.887
ALO [49]	14.758
GSA_SQP [30]	26.8258
HIIWO [50]	24.759
WOA	15.7139
HWOA	14.4646

TABLE 23. Comparison of total net gain in time obtained by HWOA with the algorithms used in the literature.

Net gain	∑ Δ(t) s
WOA/ GA	13.5549
WOA/ PSO	24.719
WOA/DE	3.3476
WOA/HS	4.7487
WOA/SOA	19.3088
HWOA/AIS	0.4224
HWOA/ALO	0.2934
HWOA/GSA-SQP	12.3612
HWOA/HIIWO	10.2994
HWOA/WOA	1.2493

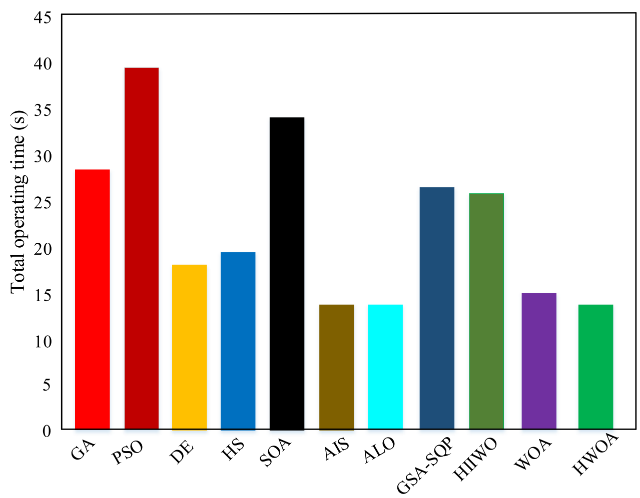

FIGURE 19. Graphical representation of optimized total operating time of the WOA with the literature for test system 5.

The optimal TDS and PS for DOCRs accomplished by the suggested HWOA is specified in Table 21. Table 22 gives the relative result of the suggested HWOA with other published algorithms cited in the literature. The convergence characteristic for overall operating time obtained for the test system 5 in the simulation is presented in Fig. 18, showing that the convergence is faster and yields an improved value for the objective function in fewer iterations. The assessment of the overall operating time yields by the suggested HWOA in term of graphical representation is shown in Figure 19 with other published technique which show values of optimized total operating time. The advantage in total net gain time obtained by the suggested HWOA is presented in Table 23 that show the dominance of the HWOA algorithm over recent published method.

VII. CONCLUSION

In this paper, the hybrid metaheuristic algorithms based on WOA algorithm was proposed. The proposed approaches integrate SA algorithm with the global search of WOA. SA was employed in the proposed approaches following the hybrid model known as LTH. In LTH, SA was used as a local search operator around the selected search agents in order to search the neighborhood of the best solution after each iteration of WOA. 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 HWOA, it has been applied to five different systems, which include the IEEE 3-bus 8-bus, 9-bus, 15-bus and 30-bus test systems. The results obtained validate that the proposed HWOA is an effective and reliable tool for the coordination of directional overcurrent relays. Moreover, the results obtained using HWOA are better than those obtained using a native WOA and number of well-known and up-to-date algorithms stated in literature.

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