Optimal Co-Ordination of Directional Overcurrent Relays in Distribution Network Using Whale Optimization Algorithm

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Abstract Modern power distribution networks are incredibly complex due to the growing incorporation of distributed generators in the past few years. The coordination of Directional Overcurrent Relays (DORs) in interconnected systems with many relays is significantly hindered by this complexity. In a nonlinear and constrained optimization problem, optimal DOR coordination is essential for protecting such

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complex systems and necessitates rigorous constraints. In order to address the optimal coordination problems of DORs, this study suggests using the Whale Optimisation Algorithm (WOA), a bio-inspired metaheuristic technique. WOA can optimize the fitness function in electrical engineering applications by taking insights from the humpback whales' hunting strategies. Using various fault data from 3-bus, 9-bus, and 30-bus standard systems, the effectiveness of WOA in promoting optimal DOR coordination is assessed. The main objective is to delineate the implementation of WOA to deal with DOR coordination problems. As a result, we are not comparing WOA's performance against any currently used algorithms. Rather, we use three case studies to test the algorithm's effectiveness with various population sizes and maximum iterations. The outcomes convincingly show that WOA is highly efficient in reducing the total period that primary relays are required to operate.

Keywords Bio-inspired algorithm · Operating time · Overcurrent relay coordination · Whale optimization algorithm

1 Introduction

When used in combination with fuses, reclosers, and Circuit Breakers (CBs), Overcurrent Relays (OCRs) are a common kind of protection for traditional radial distribution networks. The incorporation of Distributed Generators (DGs) into distribution networks has grown in recent years because of the significant technological, economic, and environmental advantages that DGs provide. The incorporation of DGs, on the other hand, transforms the radial topology of the traditional distribution network into an interconnected framework, leading to bidirectional power flow [1, 2]. A significant influence on the amount of the short-circuit current is exerted by the kind of DG and penetration level of DGs. When it comes to protecting such complex networks quickly and reliably, Directional Overcurrent Relays (DORs) are typically preferred over simple OCRs [3]. In order to improve the overall effectiveness of the protection scheme, DORs must work together in the most efficient manner possible. In transmission and distribution infrastructure, DORs are commonly employed for main protection, and they can also be used to safeguard distance relays in transmission systems as a backup protective device [4, 5].

The DORs might become necessary in order to achieve fault zone differentiation in the ring main, double-end fed, parallel feeder, and multi-looped systems. The primary function of a DOR is to identify a fault as soon as it occurs if it occurs within its

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operational zone without any intended delay [6]. Primary protection is defined as the identification of a problem inside the specified zone without the use of any intended delay. Occasionally, primary protection neglects to eliminate a problem due to the failure of relays and/or CBs to function properly. It is necessary to have backup protection in place to correct the problem. Backup protection is an extra layer of security offered to a spot that only triggers after an intended delay if the main security of that part neglects to function properly [7]. In the coordination of DORs, the task of determining the most appropriate relay settings, specifically the Time Multiplier Setting (TMS) and the Plug Setting (PS), in such a way that the main relay reacts quicker than any other relays in the system is referred to as coordination. To minimize the overall working time of all primary relays and prevent miscoordination between primary and backup relay pairs, the coordination of DORs must find the optimal TMS and PS values for each relay while taking into consideration specific constraints. In the event of a failure of the main relay or the related circuit breaker, backup relays must be activated after a certain time interval, ensuring that the Primary/Backup (P/B) relay pairs are operated in the correct sequential order [8, 9].

Several ways to achieve the best possible coordination of DORs utilized for the protection of meshed distribution networks have been described in the scientific research literature. For relay coordination, it was common to practice in the past to use trial-and-error approaches [10]. Trial and error procedures, on the other hand, are hampered by the demand for many iterations and the sluggish rate of convergence. Topological modelling was used to provide optimal coordination of DORs, which were later implemented [11, 12]. When contrasted to trial-and-error procedures, topological analysis-based methods specify a minimum number of iterations to arrive at an appropriate solution. Nevertheless, using the topological analysis approach, it is not assured that the global optimal of TMS and PS of DORs would be obtained. In subsequent phases, numerous optimization algorithms for overcoming the coordination challenges of DORs were suggested, with the most prominent programming. Simplex [13], two-phase simplex [14], Sequential Quadratic Programming (SQP) [15], and dual simplex [16] are examples of classical optimization methods that are based on Linear Programming (LP) methods [17]. These approaches are fast and straightforward. However, because the operating time of the DOR is a linear function of the TMS, the LP-based optimization strategies are only useful for optimizing the TMS in this case. Because DOR management is a nonlinear problem, Nonlinear Programming (NLP) methods such as the gradient search technique [18], random search technique, and sequential quadratic programming [19] have been suggested in previous studies to defeat the shortcomings of LP-based approaches. It is possible to tune both the TMS and PS of DORs simultaneously using an NLP-based optimization technique. When it comes to addressing the DOR coordination problem, NLP-based solutions outperform LP techniques by a wide margin. However, both traditional optimization strategies have the potential to become stuck at the local optima and struggle to reach the global optima as a result. Furthermore, as the scale of the system grows, the pace of convergence of such optimization techniques becomes more and slower. As a result, over the last few decades, heuristic methods have emerged as useful tools for solving the relay coordination problem. There are

a variety of methods available, including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolutionary (DE) algorithm, Backtracking Search Algorithm (BSA), Artificial Bee Colony (ABC) algorithm, Ant Colony Optimization (ACO), Biogeography-Based Optimization Algorithm (BBOA), Gravitational Search Algorithm (GSA), Teaching Learning-Based Optimization (TLBO), Grey Wolf Optimizer (GWO), Cuckoo Search (CS), and Harmony Search (HS) algorithm [20–24]. For the coordination problem of DORs, hybrid methods are also used to improve computational speed. These methods include GA-LP, GA-NLP, BBOA-LP, GSA-SQP, PSO-SQP, and PSO-GSA. When compared with trial and error, topological, and traditional LP and NLP algorithms, such heuristic and evolutionary optimization algorithms outperform them in terms of reaching the global optimal solution. Most metaheuristic algorithms, on the other hand, need greater computing time and suffer from premature convergence. Researchers have put forth a great amount of effort to date to solve the optimal relay coordination challenges that arise in DOR networks. It seems that practically every time, the primary aim is to improve the relay settings to reduce the total Operating Time (OT) of the relays. However, the challenge of coordination between relays (P/B relay pairs) has not been properly handled so far. As a result, to close the research gap, this paper addresses both objectives, namely, optimization of coordination between P/B relay pairs and relay settings, at the same time and with better results.

Recently, a bio-inspired metaheuristic optimization technique called Whale Optimization Algorithm (WOA) for solving optimization issues was published in [25] and is described in detail. In comparison to other algorithms, WOA is made to balance the exploration and exploitation of the search area, which can improve the convergence rate and overall optimization. It is simpler to develop and utilize for many optimization problems because it only requires a few tuning parameters. It can rapidly reach an equivalent to an ideal solution in a short period due to its strong convergence rate. Compared to other optimization techniques, it is more computationally efficient and relatively simple to implement. It can solve various optimization problems, including those with one or more objectives. In addition, this algorithm is not applied to optimal coordination of directional overcurrent relay optimization problems. This motivated us to select the whale algorithm for the above-said optimization problem. Therefore, this paper uses WOA to provide the best possible coordination of DORs. The recommended algorithm's performance is tested on standard 3-, 9-, and 30-bus test power systems, with faults introduced at the midway of the lines to evaluate its effectiveness. The recommended algorithm's performance is revealed to be an optimal tool in terms of attaining the shortest overall OT of relays.

2 Optimization Problem Formulation

2.1 Objective Function

The problem of DOR can be expressed as either a linear function or a nonlinear function. In the scenario of a linear function, plug-setting has remained constant among the upper and lower bounds of the flow of current while TMS is computed; however, in the scenario of a nonlinear function, both TMS and PS are minimized at the same time in both cases. Apart from that, the quantized characterization of relay configurations increases the difficulty in coordinating the operation of the system. When it comes to solving the DOR's coordination challenge, there are primarily two objectives that must be addressed. The initial aim is to reduce the overall running time of all relays put in the network to the bare minimum, allowing the problem to be addressed in the shortest amount of time. Second, the coordination between the backup and primary relays should be retained, i.e., the backup relay would only act after a specified period if the primary relay could not function properly. The mathematical expression of the relay can be stated as follows [26].

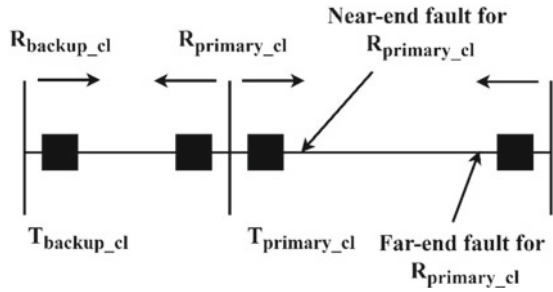$$T_{ik} = \frac{TMS_i * \beta}{\left(\frac{I_f}{PS_i \cdot \mathrm{CT}_{Rating,P}}\right)^\alpha - \delta} \tag{1}$$

$$I_f = \frac{I_{R_i,k}}{\mathrm{CT}_{Rating,P}} \tag{2}$$

where T_{ik} denotes the ith relay operating time for a fault at the kth site, $I_{R_i,k}$ denotes the fault current observed in the relay R_i for a fault at the the kth site, and I_f denotes the fault current at the Current Transformer (CT) primary terminal. PS_i denotes the PG of the relay R_i above which it begins to operate, while TMS_i denotes the TMS of the relay R_i. α, β, and δ are coefficients that change depending on the characteristics of the relay. According to [26], the values of the parameters are 0.02, 0.14, and 1, respectively, as per IEC Standard 60,255–151 for Inverse Definite Minimum Time (IDMT) relays. $\mathrm{CT}_{Rating,P}$ denote the primary rating of the respective CT. The relationship between $I_{R_i,k}$ and PS_i denotes the factor that determines the degree of nonlinearity. If the fault occurs nearer to the relay, then the fault is called the near-end fault (or close-in fault), and if the fault occurs at another end of the line is called the far-end fault (or far-bus fault), as depicted in Fig. 1.

The primary objective of coordinating the DORs problem is to find the best TMS and PS values so that the overall weighted sum of all primary relays' Operation Time (OT) at their related zones is as small as possible. As a result, the objective function can be written as follows [27, 28].

$$\mathrm{Min:} f = \sum_{i=1}^{N_{cl}} T_{cl_{in},P}^i + \sum_{j=1}^{N_{far}} T_{far_{bus},P}^j \tag{3}$$

$$T_{cl_{in},P}^{i} = \frac{0.14 \cdot \text{TMS}^{i}}{\left(\frac{I_f^i}{textPS^i \cdot \text{CT}_{Rating,P}^i}\right)^{0.02} - 1} \tag{4}$$

$$T_{far_{bus},P}^{j} = \frac{0.14 \cdot \text{TMS}^{j}}{\left(\frac{I_f^j}{textPS^j \cdot \text{CT}_{Rating,P}^j}\right)^{0.02} - 1} \tag{5}$$

where N_{cl} denotes the number of relays responding to a near-end fault and N_{far} denotes the number of relays responding to far-end faults.

2.2 Constraints

There are specific limits on how long the relay can operate that must be met for the relay to function properly. To function within the constraints, the TMS and PS should be constrained. The TMS has a boundary requirement that should be met for the relay to operate quickly and correctly. The relay must not cross the bounds. It should function within the TMS's upper (*ub*) and lower (*lb*) limits. As a result, the ith relay's TMS limit setting can be written as follows:

$$TMS_i^{lb} \leq TMS_i \leq TMS_i^{ub}, i = 1, 2, 3, \ldots, N_{cl} \tag{6}$$

In this paper, the *lb* and *ub* values of TMS are chosen to be 0.05 and 1.1, respectively. The relay's PS should be such that it stays quiet when the feeder is receiving peak load current, but it should function when the feeder is experiencing minimum fault current. To satisfy the above conditions, the bounds of the *i* th relay's PS can be stated as follows [27]:

$$PS_j^{lb} \leq PS_j \leq PS_j^{ub}, j = 1, 2, 3, \ldots, N_{far} \tag{7}$$

In this paper, the *lb* and *ub* values of PS are chosen to be 1.25 and 1.5, respectively. The TMS, PS, and the fault current shown by the relay determine the relay's OT. The OT is calculated using analytic formulas or standard inverse curves based on the characteristics of the relay. Each element of the objective function is constrained to be between 0.1 and 1.1. The backup relay should only be used after the primary relay has failed to prevent maloperation. It is required for the backup and primary relays' selectivity to be maintained. The Coordination Time Interval (CTI) is the summation of the OT of the circuit breaker connected with the primary relay and the overshoot time. The gap between the OT of the backup relay and the primary relay should be greater than the CTI in coordinating two overcurrent relays. The CTI can be characterized as follows [27]:

$$CTI = T_{j,k} - T_{i,k}, i = 1, 2, \ldots, N_{cl} \tag{8}$$

where $T_{j,k}$ denotes the OT of the jh B-relay for a fault at kth location within the protected zone by the ith P-relay. Thus, the constraint for CTI can be represented as follows [27]:

$$CTI \geq CTI_{min} \tag{9}$$

where CTI_{min} denotes a minimum CTI, and it is typically between 0.2 and 0.3 s. For all P/B pairs, the constraint for CTI should be met. Close-in, far-bus, and middle-point fault currents are commonly utilized, and they provide coordination for many fault scenarios.

2.3 Modified Objective Function

However, the least possible CTI between the backup and primary relays is essential for correct selection; considerably deferred backup relay operation is not preferred from the standpoint of successful relay coordination. Therefore, the objective function is adjusted to improve the CTI between primary and backup relays, as follows [29]:

$$\text{Min:} f = \alpha_1 \sum_{i=1}^{m} \sum_{k} T_{i,k}^2 + \alpha_2 \sum_{p=1}^{m_p} \left[\Delta T_{mp} - \beta \left(\Delta T_{mp} - \left| \Delta T_{mp} \right| \right) \right]^2 \tag{10}$$

$$\Delta T_{mp} = T_{j,k} - T_{i,k} - CTI \tag{11}$$

where ΔT_{mp} denotes the difference in OT with CTI between pth pair of relays, m denotes the number of relay units, m_p denotes the number of P/B relay pairs, α_1 and α_2 denote weight factors, and β denotes factor to consider the miscoordination. If the value of β increases, the level of miscoordination decreases; however, it increases

the OT of the relay units. Therefore, it is necessary to select the optimal values of β. The synchronization between DORs is stated as a highly constrained and nonlinear optimization problem in which the TMS and PS of each relay are considered as design parameters. The major aim is to reduce the OTs of all P-relays, which are supposed to work to clear the faults in their respective regions after the faults are cleared.

3 Whale Optimization Algorithm (WOA)

WOA is a recently proposed metaheuristic algorithm based on swarms that have been presented for continual problems. It has been demonstrated to outperform contemporary meta-heuristic approaches in terms of overall performance [25, 30]. For example, it is simple and robust compared to other metaheuristic approaches, making it analogous to diverse nature-inspired algorithms in terms of implementation and robustness. The algorithm requires a smaller number of control parameters; in practice, only one parameter has to be fine-tuned. As depicted in Fig. 2, the humpback whale population in WOA searches for food in a multi-dimensional search space. In this model, the positions of whale populations are depicted as various decision vectors, and the range between whale populations and food relates to the level of fitness values. The three operational procedures described below are used to determine the time-dependent position of a whale population: (i) prey encircling, (ii) bubble-net attacking, and (3) prey search. The WOA is depicted in Fig. 3 in its most fundamental form.
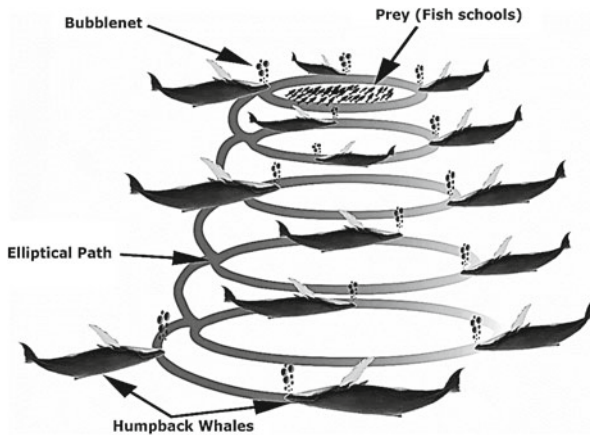
Fig. 2 Bubble-net attacking of the prey

Fig. 3 Position update of the whale using spiral strategy
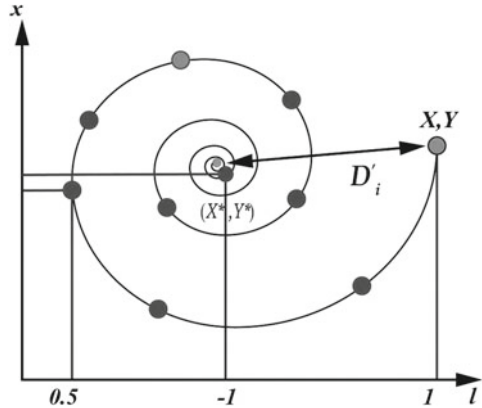
3.1 Prey Encircling

Whales can distinguish and encircle their prey while they are in their natural habitat. Because the location of the design optimization in the search area is not known a priori, the WOA assumes that the current best candidate solution is either the target prey or very close to the best solution in the search space. The top search agent would be identified, and the remaining search agents would adjust their positions to be as close as possible to that of the top search agent. According to [25], the following equations can be used to express the behaviour described above:

$$\vec{D} = \left| \vec{C} . \vec{X^*}(t) - \vec{X}(t) \right| \tag{12}$$

$$\vec{X}(t+1) = \vec{X^*}(t) - \vec{A} . \vec{D} \tag{13}$$

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \tag{14}$$

$$\vec{C} = 2 \cdot \vec{r} \tag{15}$$

where $\vec{X^*}(t)$ denote the best position of the agent, $\vec{X}(t)$ denote the current position of the agent, t denote the current iteration, $\vec{a}$ is constant, and it varies linearly from 2 to 0, and $\vec{r}$ denotes a uniform random number between [0, 1].

3.2 Bubble-Net Attacking

For the whale's bubble-net behaviour to be described mathematically, a spiral mathematical model is used between the positions of the whale and the prey to simulate

the helical structure movement of humpback whales [25].

$$\overrightarrow{X}(t+1) = \overrightarrow{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \overrightarrow{X^*}(t) \tag{16}$$

$$\overrightarrow{X}(t+1) = \begin{cases} \overrightarrow{X^*}(t) - \overrightarrow{A} \cdot \overrightarrow{D} & \text{if } p < 0.5 \\ \overrightarrow{D}' \cdot e^{bl} \cdot \cos(2\pi l) + \overrightarrow{X^*}(t) & \text{if } p \geq 0.5 \end{cases} \tag{17}$$

where p denotes a constant which describes the logarithmic spiral shape, and l denotes a uniformly distributed arbitrary number between [–1,1].

3.3 Prey Search

For global optimization algorithms to function, if $A > 1$ or $A \leq -1$, the population is updated in accordance with the directions provided by a randomly chosen population in the role of the best population [25].

$$\overrightarrow{D} = \left| \overrightarrow{C} \cdot \overrightarrow{X_{\text{rand}}} - \overrightarrow{X} \right| \tag{18}$$

$$\overrightarrow{X}(t+1) = \overrightarrow{X_{\text{rand}}} - \overrightarrow{X} \cdot \overrightarrow{D} \tag{19}$$

where X_{rand} denotes random population position in the current iteration. Readers should refer to [25] for additional information.

4 Results and Discussions

It is verified in this paper that the WOA can be used to find the optimal coordination of directional overcurrent relays in the distribution network is considered. In this paper, there are three test cases, such as 3-bus (Case-1), 9-bus (Case-2), and 30-bus (Case-3) models, are considered. The results were presented for all three test cases. The control parameters of the WOA were taken based on the original paper, literature study, and trial and error method. The population size is 10 times the problem dimension, and the maximum number of iterations is selected as per the problem's complexity. The problem dimensions for the 3-bus test model is 6, for the 9-bus test model is 24, and for the 30-bus test model is 38. Therefore, the best population size for the 3-bus model is 60, for the 9-bus model is 240, and for the 30-bus model is 380. The value of the constant a is linearly decreased from 2 to 0, the value of l varies between [–1,1], and the value of p is a random number between [0,1]. The experimental results are discussed in three sub-sections. The sub-Sect. 1 defines the results attained by the WOA for Case-1 with different population sizes. The sub-Sect. 2 describes the

results attained by the WOA for Case-2 with different population sizes. The sub-Sect. 3 defines the results attained by the WOA for Case-3 with different population sizes. A computer with an Intel Core i5 CPU operating at 4.45 GHz and 16 GB of memory is used to execute the experiment through MATLAB software. The lower and upper bounds for all case studies are selected as per the data collected from the different literature.

4.1 Case-1: 3-Bus Test Model

As demonstrated in Fig. 4, a three-bus (B1-B3) test system with one generator (G1) and six DORs (R1-R6) is investigated. The ratings of each component, as well as line data for each component, are taken from [12, 26]. As indicated in Table 1, the fault current at each bus is computed using the provided standard data, with the event of a fault in the centre of the line being taken into consideration. Table 1 also contains the primary rating of the CT. In clearing all near-end and far-end faults, it is necessary to synchronize the settings of each of the six relays that respond. As a result, there are a total of 12 control vectors in the DORs problem, which are designated as TMS1-TMS6 and PS1-PS6, respectively. The TMS values at the lower and upper levels are 0.05 and 1.1, respectively. PS is in the range of 1.25–1.50, depending on the model. The CTI_{min} is set to its default value of 0.3 s.

As shown in Table 3, the optimal TMS and PS parameters derived by the WOA are shown. For near- and far-end faults, the OT of all primary relays is also listed in Table 3. The OTs are within an adequate level of 0.1–1.1 s, which is satisfactory. The overall OT of the P-relays is 4.8613 s. As shown in Table 4, the DORs do not have any miscoordination pairings when they are in operation. To examine the convergence behaviour of WOA, the convergence curve is depicted in Fig. 5.
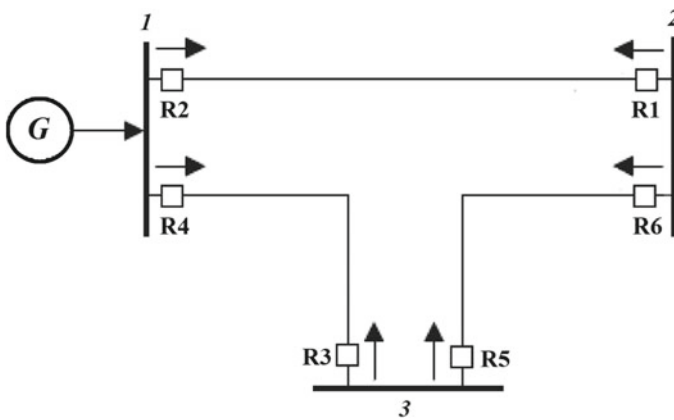

Fig. 4 Case-1: Schematic of the 3-bus test model

Table 1 Fault currents observed in the 3-bus test model

Primary relay	Fault current (A)	Backup relay	Fault current (A)	Primary rating of CT
1	9.46	5	100.63	2.06
2	26.91	4	14.08	2.06
3	8.81	1	136.23	2.23
4	37.68	6	12.07	2.23
5	17.93	3	19.20	0.8
6	14.35	2	25.90	0.8

Table 2 Fault currents for P/B relays in the 3-bus test model

Primary Relay	Fault current (A)		Backup Relay	Fault current (A)	
	Close-in	Far-bus		Close-in	Far-bus
1	9.46/2.06	14.08/2.06	5	9.46/0.8	14.08/0.8
3	8.81/2.23	12.07/2.23	6	8.81/0.8	12.07/0.8
5	17.93/0.8	25.9/0.8	4	17.93/2.23	25.9/2.23
6	14.35/0.8	19.2/0.8	2	14.35/2.06	19.2/2.06

Table 3 Optimal PS and TMS values for the 3-bus test model

Relay	N = 40				N = 60			
	TMS	PS	$OT_{Close-in}$	$OT_{Far-bus}$	TMS	PS	$OT_{Close-in}$	$OT_{Far-bus}$
1	0.0500	1.2500	0.2655	0.2025	0.0500	1.2500	0.2655	0.2025
2	0.2198	1.2500	0.6403	0.4045	0.2194	1.2500	0.6392	0.4038
3	0.0500	1.2500	0.3007	0.2353	0.0500	1.2500	0.3007	0.2353
4	0.2391	1.2500	0.6262	0.4138	0.2299	1.2500	0.6021	0.3979
5	0.1950	1.2500	0.4593	0.4059	0.1950	1.2500	0.4593	0.4059
6	0.1953	1.2500	0.4997	0.4491	0.1953	1.2500	0.4997	0.4491
OT in sec	4.9027				4.8613			

When analyzing the results obtained for two population sizes of the suggested WOA, it is evident that the WOA with a population size of 60 with 1000 iterations produces the optimal settings. In addition, the Run-Time (RT) of the WOA is also recorded in Table 4. As seen in Table 4, the RT value of WOA with a 40-population size is very much lesser than the WOA with a 60-population size. It is obvious that the algorithm with less population size takes lesser computation time. However, the results produced by the 60 population size are superior though the RT is high.

Table 4 CTI for the 3-bus test model

Faults	N = 40				N = 60			
	Relay		CTI	RT	Relay		CTI	RT
	Backup	Primary			Backup	Primary		
Close-in	5	1	0.3000	0.4905	5	1	0.3000	0.6259
	6	3	0.3000		6	3	0.3000	
	4	5	0.3283		4	5	0.3001	
	2	6	0.3805		2	6	0.3790	
Far-bus	5	1	0.3283		5	1	0.3284	
	6	3	0.3141		6	3	0.3140	
	2	6	0.4233		2	6	0.3893	
	4	5	0.3013		4	5	0.3001	
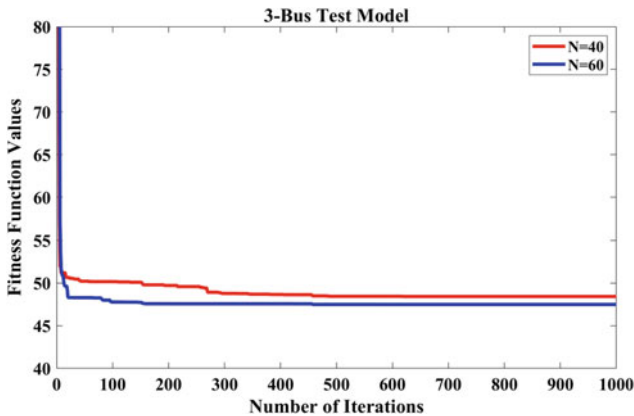
Fig. 5 Convergence curves for different population sizes (3-bus model)

4.2 Case-2: 9-Bus Test Model

The schematic of the 9-bus system is shown in Fig. 6. With the normally inverse features, and there seem to be 24 digital DORs in this case study. TMS is recorded in the range of 0.01–1.0, and PS is recorded in the range of 0.5–2.5. In this case, the CTI_{min} is fixed to a duration of 0.2 s. The value of the CT ratio is 500/1.

Short-circuit faults are formed in the centre of each line. The fault locations are labelled with the letters A-L in Fig. 6. Table 5 lists the fault currents observed in each P/B relay. In this optimization problem, there are a total of 48 decision vectors, i.e., TMS1-TMS24 and PS1-PS24 are considered. Due to problem complexity, the maximum iteration is selected as 2000.
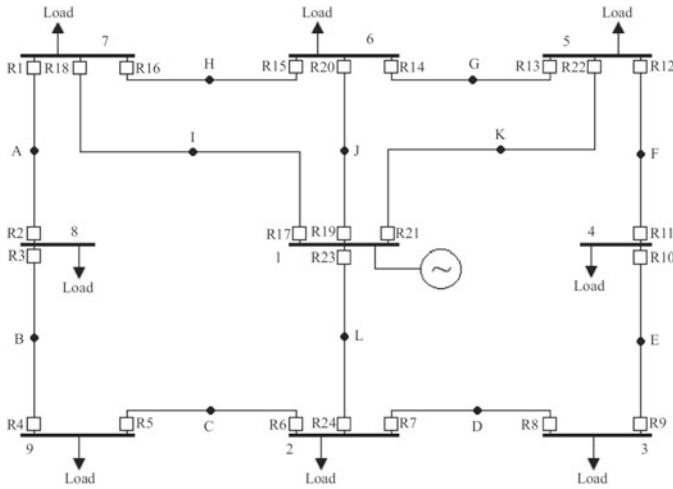
Fig. 6 Schematic of the 9-bus test model

Table 5 Fault currents in P/B relays for Case-2

Location	P-Relay	B-Relay	$I_{f,p}$ (A)	$I_{f,s}$ (A)	Location	P-Relay	B-Relay	$I_{f,p}$ (A)	$I_{f,s}$ (A)
A	1	15	24,779	9150	G	13	11	16,087	3088
	1	17	24,779	15,632		13	21	16,087	13,000
	2	4	8327	8327		14	16	18,213	6285
B	3	1	16,390	16,390		14	19	18,213	11,934
	4	6	144,671	14,671	H	15	13	18,218	6285
C	5	3	9454	9454		15	19	18,218	11,935
	6	8	23,280	4777		16	2	16,087	3088
	6	23	23,280	18,507		16	17	16,087	13,000
D	7	5	23,280	4777	I	18	2	8161	2426
	7	23	23,280	18,507		18	15	8161	5736
	8	10	9454	9454	J	20	13	9286	4644
E	9	7	15,304	15,304		20	16	9286	4644
	10	12	16,490	16,490	K	22	11	8161	2426
F	11	9	8326	8326		22	14	8161	5736
	12	14	24,779	24,779	L	24	5	6149	3075
	12	21	24,779	24,779		24	8	6149	3075

The suggested WOA is used to solve the DORs coordination problem, as discussed earlier. Table 6 shows the optimal TMS and PS values, as well as the optimal objective function value. The OT values are within an acceptable range of 0.1–1.1 s in all

primary relays. Comparisons are made between the optimum values of decision variables (TMS and PS) and OT using the results produced by WOA with two different population sizes, such as 150 and 250. Table 7 displays the respective CTI values. When comparing the WOA with two different population sizes, the results produced by WOA with 250 population size demonstrate that the total OT of primary DORs is lowered. As can be seen in Table 7, the optimal outcomes provide no miscoordination. Furthermore, while utilizing the WOA with a 250-population size, the CTI improves since the total CTI values are lowered when compared to WOA with a 150-population size, hence improving the CTI. To examine the convergence behaviour of WOA, the convergence curve is plotted and depicted in Fig. 7. From Fig. 7, it is observed that the convergence rate of the WOA with large population size is higher than lower population size.

4.3 Case-3: 30-Bus Test Model

The IEEE 30-bus system is taken into consideration to assess the efficacy of the WOA in tackling a larger power system problem. As illustrated in Fig. 8, the system can be thought of as a meshed sub-transmission/distribution system having distributed-generated units interconnected. For the 30-bus test model, a total of 38 DORs with normal inverse characteristics are examined, with one at every end of the lines. Table 8 shows the short-circuit current values for close-in faults. TMS is measured in the range of 0.1–1.1, and PS is measured in the range of 1.5–6. The CT ratio for each relay was supposed to be 1000/5. The CTI_{min} value has been set to 0.3 s. Due to complexity, the maximum iteration is selected as 5000.

Table 9 shows the results achieved by WOA with two different population sizes, such as 300 and 400. Table 10 illustrates the CTI obtained from the optimum TMS and PS values, proving there is no miscoordination. This shows that results produced using WOA with a 400-population size are superior to those acquired using WOA with a 300-population size, as can be seen in the table. This demonstrates that the suggested WOA may be utilized to effectively handle the DORs' coordination problem for large-scale power systems. The RT values are recorded, and it is obvious that WOA with a 400-population size takes more computation time than WOA with a 300-population size.

To observe the convergence behaviour of WOA while handling large-scale problems, the convergence curve is shown in Fig. 9. From Fig. 9, it is noticed that the convergence rate of the WOA with large population size is higher than the lower population size. The suggested WOA with a larger population size outperforms the WOA with a lower population size in terms of producing more stable and better solutions for all three test systems.

Table 6 Optimal PS and TMS values for the 9-bus test model

Relay	N = 40			N = 60		
	TMS	PS	$OT_{primary}$	TMS	PS	$OT_{primary}$
1	0.5396	1.4796	1.0383	0.5463	1.3679	1.0274
2	0.4032	0.5653	0.8064	0.2645	1.0616	0.6542
3	0.4545	1.3600	0.9683	0.4353	1.4819	0.9538
4	0.4531	1.1242	0.9410	0.4070	0.6595	0.7226
5	0.3845	1.2198	0.9553	0.3965	1.1589	0.9665
6	0.5696	1.3054	1.0762	0.4844	1.1781	0.8887
7	0.5691	1.3172	1.0780	0.5593	1.4422	1.0881
8	0.3987	1.1234	0.9610	0.4558	0.5537	0.8722
9	0.4669	1.1836	0.9725	0.3993	1.2013	0.8355
10	0.4353	1.4644	0.9482	0.5203	0.7805	0.9368
11	0.5207	0.5000	1.0038	0.2507	1.5719	0.7261
12	0.5593	1.2179	1.0178	0.5337	1.3684	1.0039
13	0.4566	1.1768	0.9346	0.5360	1.0687	1.0650
14	0.4927	1.2430	0.9869	0.5119	1.1360	0.9979
15	0.4620	1.4353	0.9680	0.5482	1.2777	1.1075
16	0.3884	1.3391	0.8282	0.3830	1.4219	0.8331
17	0.5960	1.2268	0.0000	0.5747	1.3607	–
18	0.4099	1.2405	1.0849	0.2316	1.3989	0.6437
19	0.4872	1.4617	0.0000	0.5814	1.1687	–
20	0.4501	1.2310	1.1297	0.4522	1.3215	1.1663
21	0.5639	1.3666	0.0000	0.5751	1.2284	–
22	0.4577	1.4813	1.3034	0.3860	1.0707	0.9652
23	0.6367	1.2716	0.0000	0.6361	1.4368	–
24	0.4843	1.1824	1.4140	0.2192	1.4098	0.6931
OT in sec	2041694			1814768		

4.4 Discussions

Finding the best settings for these devices to save operation time and improve the durability of power systems is the objective of DOCRs' optimal coordination. This is a challenging, nonlinear optimization problem with many constraints. WOA may be a superior option for this problem compared to other algorithms for the following reasons. (i) WOA, which uses many solutions (whales) in each iteration and changes them in accordance with the best solutions discovered, is a population-based algorithm. Compared to conventional gradient-based optimization approaches, this enables it to explore the solution space more completely and decreases the likelihood of getting stuck in local minima, (ii) Unlike what is frequently the case in relay

Table 7 CTI for the 9-bus test model

| N = 40				N = 60			
Relay		CTI	RT	Relay		CTI	RT
Backup	Primary			Backup	Primary		
15	1	0.2001	9.8596	15	1	0.3763	13.5062
17	1	0.2088		17	1	0.2162	
4	2	0.3389		4	2	0.2000	
1	3	0.2008		1	3	0.2000	
6	4	0.3006		6	4	0.2985	
3	5	0.2220		3	5	0.1999	
8	6	0.2000		8	6	0.2000	
23	6	0.2018		23	6	0.4378	
5	7	0.2029		5	7	0.2000	
23	7	0.2000		23	7	0.2383	
10	8	0.1999		10	8	0.2344	
7	9	0.2544		7	9	0.4073	
12	10	0.2000		12	10	0.2002	
9	11	0.2000		9	11	0.3092	
14	12	0.2304		14	12	0.2498	
21	12	0.2043		21	12	0.2000	
11	13	0.4793		11	13	0.2000	
21	13	0.3663		21	13	0.2139	
16	14	0.2001		16	14	0.2058	
19	14	0.2005		19	14	0.3110	
13	15	0.3499		13	15	0.3777	
19	15	0.2194		19	15	0.2014	
2	16	0.3242		2	16	0.2000	
17	16	0.4967		17	16	0.4907	
2	18	0.2000		2	18	0.5563	
15	18	0.4390		15	18	1.0667	
13	20	0.3859		13	20	0.5318	
16	20	0.2469		16	20	0.2357	
11	22	0.2644		11	22	0.5744	
14	22	0.2142		14	22	0.5489	
5	24	0.2229		5	24	0.9422	
8	24	0.2000		8	24	0.6005	
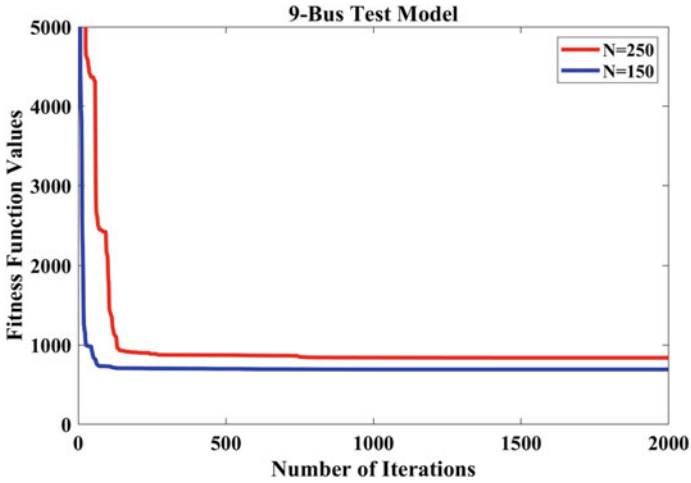
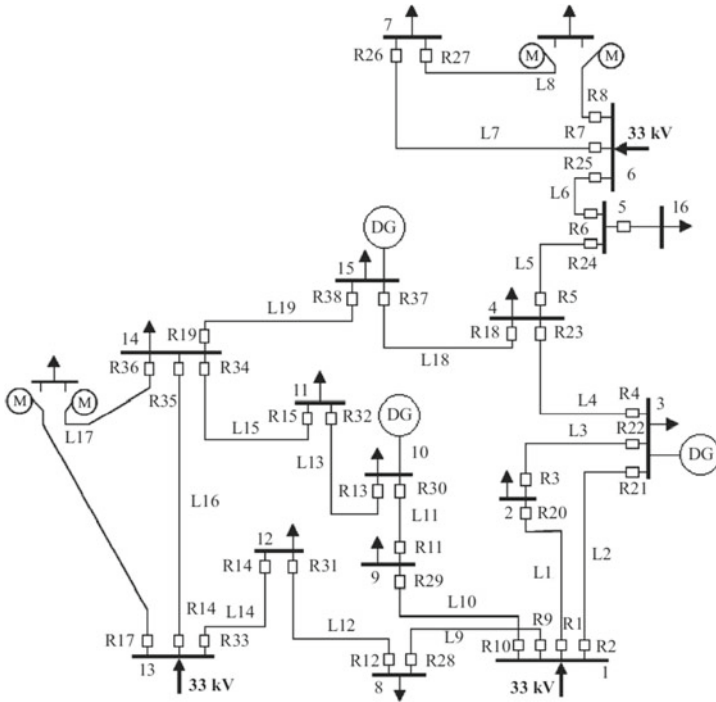**Fig. 7** Convergence curves for different population sizes (9-bus model)

Fig. 8 Schematic of the 30-bus test model

coordination problems, WOA does not demand that the problem be differentiable or even continuous. This provides it with a considerable edge over techniques like the Newton–Raphson approach, which relies on the gradient of the problem, (iii) Compared to more sophisticated algorithms, WOA is simpler to use and is not as subject to overfitting because it has few parameters that need to be tuned, (iv) WOA has demonstrated strong scalability characteristics, indicating that it can successfully address issues of varied sizes. This is important since relay coordination problems can have a lot of different factors and limitations.

Comparing WOA with different sizes of populations and numbers of iterations can show how well it works and help tune its settings for the DOCR coordination problem. Note that an increased population size with more iterations usually leads to better solutions but at the cost of using more computing resources. Because of this, it is important to find an equilibrium that fits the needs and limits of your application.

5 Conclusions

Coordinating DORs in a distributed system is a challenging nonlinear optimization problem addressed in this research. The objective is to reduce the total OTs of all primary relays required to clear faults at their assigned locations. The TMS and the PS of each relay, which serves as the variables in this optimization problem, are two crucial choice criteria. The bus model's complexity causes the dimensionality to rise. Examples include the 3-bus model, which provides a six-dimensional problem, and the 9-bus and 30-bus models, which contain 24 and 38 dimensions. Due to multimodal landscapes' enormous complexity and complicated nature, it is extremely difficult to

Table 8 Fault currents in P/B relay for Case-3

P-Relay	B-Relay	$I_{f,p}$ (A)	$I_{f,s}$ (A)	P-Relay	B-Relay	$I_{f,p}$ (A)	$I_{f,s}$ (A)
3	1	4086.7	4086.7	9	20	7212.6	1103.5
4	2	5411.2	2138.8	10	20	7339.3	1095.8
22	2	4333	2147	1	21	7665.3	698.8
4	3	5411.2	3272.5	9	21	7212.6	721.2
21	3	5411.8	3243.6	10	21	7339.3	716.1
5	4	4960.8	3001.3	20	22	3481.5	3481.5
18	4	4719.4	3002.1	21	23	5411.8	2193.5
6	5	2416	2416	22	23	4333	2204.6
7	6	5669	1790.9	18	24	4719.4	1717.7
8	6	5607	1774.8	23	24	3689.7	1724.2
27	7	1472.3	1472.3	24	25	2695	2695
26	8	1026.8	1026.8	1	28	7665.3	1552

(continued)

Table 8 (continued)

P-Relay	B-Relay	$I_{f,p}$ (A)	$I_{f,s}$ (A)	P-Relay	B-Relay	$I_{f,p}$ (A)	$I_{f,s}$ (A)
12	9	5034.9	5034.9	2	28	7985.7	1545.8
11	10	3457.1	3457.1	10	28	7339.3	1538
13	11	3727.3	2875	1	29	7665.3	1380.6
14	12	2906.5	2906.5	2	29	7985.7	1375.2
15	13	2660.5	2660.5	9	29	7212.6	1379
16	14	6185.6	1668.1	29	30	2518.9	2518.9
17	14	7492.9	1641.1	28	31	2036.8	2036.8
19	15	5445.2	1527.3	30	32	2998.8	2149
35	15	4222	1533.2	31	33	3263.6	3263.6
36	15	6420.2	1509.7	32	34	2930.4	2930.4
19	16	5445.2	3128.3	17	35	7492.9	1885.4
34	16	5796.6	3123.9	33	35	6456.2	1954.5
36	16	6420.2	3052.4	16	36	6185.6	490.9
19	17	5445.2	801.3	33	36	6456.2	500.6
34	17	5796.6	800.1	5	37	4960.8	1961
35	17	4222	794	23	37	3689.7	1968.5
38	18	3133.2	2292.2	34	38	5796.6	1886.8
37	19	3788.9	2940.9	35	38	4222	1896.7
2	20	7985.7	1053.9	36	38	6420.2	1867.7

Table 9 Optimal PS and TMS values for the 30-bus test model

Relay	N = 40			N = 60		
	TMS	PS	$OT_{primary}$	TMS	PS	$OT_{primary}$
1	0.4545	3.1060	1.2345	0.4300	3.7593	1.2665
2	0.3491	2.8194	0.8976	0.3975	3.7308	1.1462
3	0.3693	3.1515	1.3573	0.3312	3.5703	1.3059
4	0.4115	2.8116	1.2437	0.4382	2.2366	1.1999
5	0.4076	2.5546	1.2268	0.3612	3.5775	1.2806
6	0.3341	2.6194	1.5068	0.3607	2.9170	1.7516
7	0.4875	3.2885	1.5505	0.1956	3.6755	0.6566
8	0.3335	1.9492	0.8526	0.2965	3.5927	0.9897
9	0.5983	3.9446	1.8509	0.4684	2.2033	1.1404
10	0.4803	2.9998	1.3092	0.3544	3.7711	1.0658
11	0.4006	3.0418	1.5861	0.3091	3.3825	1.3049

Table 9 (continued)

Relay	N = 40			N = 60		
	TMS	PS	OT$_{primary}$	TMS	PS	OT$_{primary}$
12	0.4253	2.3212	1.2194	0.2845	3.4124	0.9766
13	0.3820	3.1498	1.4777	0.3594	2.2864	1.1739
14	0.2994	2.7847	1.2475	0.1720	3.6088	0.8522
15	0.3583	2.6108	1.5154	0.2477	2.8316	1.1035
16	0.4812	3.2821	1.4683	0.3515	3.6347	1.1248
17	0.3879	3.2718	1.0869	0.4244	2.9792	1.1440
18	0.3337	2.6775	1.0501	0.2753	3.3028	0.9609
19	0.4292	3.0461	1.3417	0.3590	3.4523	1.1918
20	0.3427	2.6882	1.2602	0.2962	2.3907	1.0239
21	0.4256	2.6480	1.2523	0.3506	2.3450	0.9790
22	0.4289	2.6350	1.3952	0.3107	3.4814	1.1681
23	0.3777	2.3734	1.2629	0.3142	3.5574	1.3145
24	0.3350	2.9221	1.5107	0.2298	3.2147	1.1063
25	0.4311	2.8751	0.0000	0.3235	3.5868	-
26	0.3213	1.5000	1.8052	0.1808	2.9973	2.3387
27	0.4306	3.0602	3.4039	0.3468	1.5000	1.5020
28	0.2267	3.2851	1.3869	0.4231	1.5000	1.5167
29	0.4278	2.8702	1.9951	0.3174	3.4029	1.6759
30	0.4621	3.1394	2.0365	0.4269	3.1829	1.8986
31	0.4459	2.5311	1.6439	0.3054	3.1830	1.2865
32	0.4499	2.8409	1.8887	0.4260	2.8187	1.7793
33	0.4032	3.9091	1.3089	0.4031	2.8416	1.1333
34	0.4777	3.2525	1.4956	0.3989	3.8942	1.3633
35	0.3561	2.4247	1.1271	0.2341	3.6121	0.9119
36	0.3348	1.5000	0.7417	0.3219	1.5000	0.7132
37	0.3036	2.5729	1.0434	0.3693	3.1141	1.4060
38	0.3362	2.5866	1.2833	0.2975	2.7390	1.1735
OT in sec.	2041694			4592653		

reduce associated cost functions. We use the WOA to discover the best DOR coordination to address this. The WOA successfully avoids frequent errors, including premature convergence to inferior solutions and exhibits improved performance in multimodal situations. The WOA was additionally tested across various population sizes in a sensitivity analysis. The results showed that larger population sizes produced the best outcomes while raising the RT value. This highlights the WOA's capacity to deal with the difficult job of DOR coordination among remote networks and offers a viable path for further study and application. When handling these

Table 10 CTI for the 30-bus test model

N = 40				N = 60			
Relay		CTI	RT	Relay		CTI	RT
Backup	Primary			Backup	Primary		
1	3	0.2999	68.1456	1	3	0.4422	87.9689
2	4	0.5648		2	4	1.4148	
2	22	0.4080		2	22	1.4370	
3	4	0.3001		3	4	0.3000	
3	21	0.2999		3	21	0.5298	
4	5	0.4646		4	5	0.3002	
4	18	0.6411		4	18	0.6197	
5	6	0.3011		5	6	0.3008	
6	7	0.3289		6	7	1.5693	
6	8	1.0409		6	8	1.2545	
7	27	0.7972		7	27	0.4554	
8	26	0.5823		8	26	3.4554	
9	12	0.9985		9	12	0.3368	
10	11	0.3000		10	11	0.3000	
11	13	0.3000		11	13	0.3000	
12	14	0.3459		12	14	0.5023	
13	15	0.3144		13	15	0.3000	
14	16	0.4211		14	16	0.3001	
14	17	0.8314		14	17	0.3095	
15	19	0.9701		15	19	0.5387	
15	35	1.1764		15	35	0.8118	
15	36	1.5956		15	36	1.0378	
16	19	0.7821		16	19	0.4699	
16	34	0.6303		16	34	0.3000	
16	36	1.4166		16	36	0.9773	
17	19	4.9723		17	19	7.3382	
17	34	11.9825		17	34	8.6861	
17	35	12.8853		17	35	9.4062	
18	38	0.2998		18	38	0.3561	
19	37	0.8350		19	37	0.3030	
20	2	2.6423		20	2	1.4567	
20	9	1.4610		20	9	1.3182	
20	10	2.0356		20	10	1.4138	
21	1	9.4819		21	1	4.8623	
21	9	7.7675		21	9	4.5373	

(continued)

Table 10 (continued)

N = 40				N = 60			
Relay		CTI	RT	Relay		CTI	RT
Backup	Primary			Backup	Primary		
21	10	8.5363		21	10	4.7075	
22	20	0.3001		22	20	0.3059	
23	21	0.4485		23	21	0.9528	
23	22	0.3000		23	22	0.7550	
24	18	1.1014		24	18	0.6599	
24	23	0.8810		24	23	0.3000	
25	24	0.4128		25	24	0.5818	
28	1	0.5959		28	1	0.5059	
28	2	0.9414		28	2	0.6306	
28	10	0.5409		28	10	0.7167	
29	1	2.1479		29	1	1.8529	
29	2	2.5001		29	2	1.9907	
29	9	1.5360		29	9	1.9841	
30	29	0.3011		30	29	0.4671	
31	28	0.8241		31	28	0.2999	
32	30	0.2998		32	30	0.3000	
33	31	0.3032		33	31	0.2999	
34	32	0.2997		34	32	0.3000	
35	17	0.7240		35	17	0.5478	
35	33	0.4546		35	33	0.4968	
36	16	3.2667		36	16	3.4282	
36	33	3.2443		36	33	3.2449	
37	5	0.3406		37	5	0.9475	
37	23	0.3000		37	23	0.9061	
38	34	0.2998		38	34	0.3000	
38	35	0.6610		38	35	0.7443	
38	36	1.0681		38	36	0.9640	

complicated cases, the persuasive results demonstrate that WOA outperforms. So WOA is an intriguing alternative to the standard optimizers that are widely employed in a wide range of real-world complex power system problems.
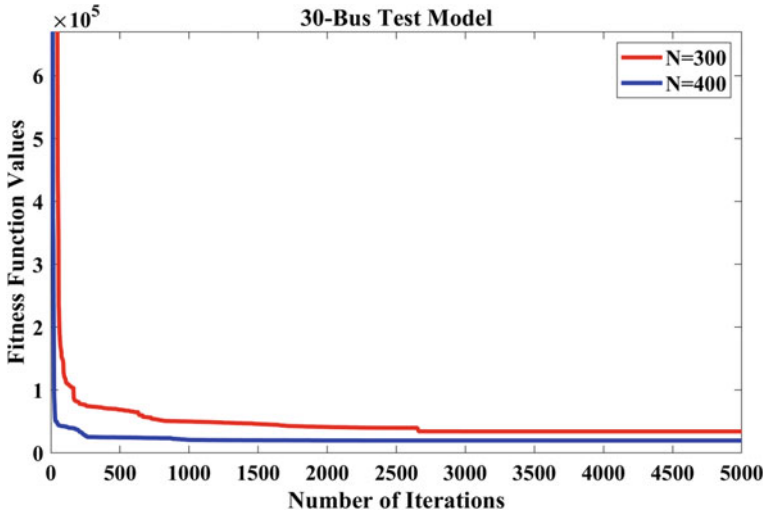
Fig. 9 Convergence curves for different population sizes (30-bus model)

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