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Analysis of War Optimization Algorithm in a Multi-Loop Power System Based on Directional Overcurrent Relays

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Abstract: In electrical power systems, ensuring a reliable, precise, and efficient relay strategy is crucial for safe and trustworthy operation, especially in multi-loop distribution systems. Overcurrent relays (OCRs) have emerged as effective solutions for these challenges. This study focuses on optimizing the coordination of OCRs to minimize the overall operational time of main relays, thereby reducing power outages. The optimization problem is addressed by adjusting the time multiplier setting (TMS) using the War Strategy Optimization (WSO) algorithm, which efficiently solves this constrained problem. This algorithm mimics ancient warfare strategies of attack and defense to solve complex optimization problems efficiently. The results show that WSO provides superior performance in minimizing total operating time and achieving global optimum solutions with reduced computational effort, outperforming traditional optimization methods (i.e., SM, HPSO, GA, RTO, and JAYA). The proposed algorithm shows a net time gains of 7.77 s, 2.57 s, and 0.8484 s when compared to GA, RTO, and JAYA respectively. This robust protection coordination ensures better reliability and efficiency in multi-loop power systems.

Keywords: directional over current relay; optimization; time multiplier setting; protection coordination; multi-loop power system

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1. Introduction

1.1. Inspiration and Motivation

Traditional distribution systems are primarily single-loop (radial), which means that electricity travels in a single path from the substation to the load. Overcurrent relays (OCR) is a well-known and inexpensive way of protecting single-loop systems. With the rise in renewable energy-based distributed generators (DGs) at the distribution voltage level, there has been a shift towards multi-loop (interconnected) networks (DGs) [1]. When it comes to DG-integrated mesh networks (multi-loop systems), traditional OCR-based protection methods often fall short [2]. To protect these multi-loop systems with DG integration, directional over current relays (DOCRs) are considered a practical and inexpensive choice [3].

In a power protection mechanism, the primary relay quickly separates the defective portion to reduce damage to the component. If the primary relay is unable to isolate the defective part, the backup relay should trip it after a specific amount of time. DOCRs have two settings: a plug setting (PS) and a time multiplier setting (TMS). The total effectiveness of these protection mechanisms is strongly dependent on the efficient coordination of DOCRs. For many years, protection engineers have struggled to coordinate DOCRs.

The employment of optimization techniques is the ideal solution for dealing with the DOCR coordination challenge [4]. Furthermore, the configuration of any DOCRs must be coordinated effectively with other DOCRs to ensure the protection of adjacent devices. The implementation of this scheme may lead to a substantial increase in the complexity of the coordination problem.

1.2. Literature Review

To elucidate this complex issue, various methodologies have been reported in the literature. Traditional methods for DOCR coordination include the trial-and-error approach [5], curve-fitting methods [6], graph-theoretical methods [7], the backward induction approach [8], and topological investigation [9]. However, these algorithms often exhibit poor convergence rates and may not provide an ideal solution. Recently, numerous optimization methods have been presented to address DOCR coordination issues with greater efficiency. Linear programming (LP) optimization techniques, such as simplex [10] and dual simplex [11], are well-known for their speed and simplicity in coordinating DOCRs. These methods, however, can only optimize the TMS, which is a straight-line function of the relay's time of operation. Sequential quadratic programming, a nonlinear algorithm (NLP), outperforms LP approaches in optimizing both the PS and TMS of DOCRs [12]. All these conventional approaches have slow convergence rates and the potential to become locked in local minima.

Various advanced metaheuristic and nature-inspired optimization approaches have been employed to solve the optimal coordination problems of DOCRs. These include combinations of evolutionary algorithms and LP [13], a modified water cycle algorithm [14], a seeker optimization algorithm (SOA) [15], a teaching–learning-based algorithm (TLB) [16], an ant–lion optimization algorithm [17], a chaotic differential evolution algorithm [18], a hybrid particle swarm optimization algorithm [19], an artificial bees colony algorithm [20], a differential evolution algorithm [21], an improved group search optimization algorithm [22], a mixed integer linear programming (MILP) algorithm [23], a firefly algorithm (FA) [24], a modified electromagnetic field optimization algorithm [25], a biogeography-based optimization method [26], hybrid whale optimization (HWO) [27], a symbiotic organism search algorithm [28], a combination of an evolutionary algorithm and linear programming [29], and an oppositional JAYA algorithm [30]. In [31], the five most efficient metaheuristic optimization techniques employed for DOCR coordination were evaluated. In comparison to LP and NLP algorithms, these techniques typically yield superior results in locating the global optimum; however, they are frequently plagued by premature convergence and computational complexity. A more efficient optimization technique, hybrid particle swarm optimization (HPSO), has been recently proposed to address DOCR coordination problems [32,33]. Simulation results in single and multi-loop power distribution systems have illustrated the HPSO method's superiority in attaining the minimum total operating time in comparison to existing methods. The Harris Hawk optimization (HHO) technique, which is renowned for its distinctive sieging and hunting capabilities, has also been applied to DOCR coordination problems [34]. This application has demonstrated superior convergence and robustness in comparison to other state-of-the-art algorithms. Problems with OCR coordination in distribution networks with one or more loops have been addressed using the JAYA algorithm [35]. Its advantages include a decrease in computing time and a reduction in iterations required to approach global optimal values. In order to achieve global minima, the whale optimization algorithm (WOA) [36] was used. This technique is based on the bubble-net hunting strategy used by humpback whales.

One more effective optimization method for OCR optimum coordination is the bio-inspired rooted tree algorithm [37]. The marine predators' algorithm [38], the slime mold algorithm [39], hybrid DA-PSO optimization algorithm [40], and machine learning approaches [41,42]. In [43–46] different kind of topologies and optimization methods has been used for the efficient optimization to solve DOCR coordination problems and multi-objective optimal power flow issues in power systems. The DOCR problem in a multisource network can be represented as an optimization challenge within electrical power systems. The limitation of the prior optimization methods, including metaheuristic approaches, lies in their potential to combining standards that may not achieve optimality across all scenarios, but rather are restricted to a local optimal value. To address this problem, this paper examines a novel application of the WSO algorithm strategy to accurately determine the optimal DOCR coordination in comparison to other contemporary algorithms.

1.3. Contribution and Paper Organization

In this study, a novel application of a metaheuristic algorithm war strategy optimization (WSO) algorithm [47], inspired by the 'war strategies' of ancient times, is used in a multi-loop power system to reduce the time of operation of each OCR in order to reduce the total time of operation thus reducing the computational complexity. This algorithm also helps to identify the best coordination of DOCRs. The unique approach of WSO, inspired by ancient warfare strategies, offers a good solution by balancing exploration and exploitation in search spaces. This paper introduces a novel application of WSO for optimizing directional overcurrent relay settings, demonstrating significant improvements in efficiency and computational performance compared to traditional methods. The main driving force behind WSO is the tactical deployment of army troops throughout the conflict. Each soldier in a combat plan is dynamically moved toward the global best optimal value via an optimization procedure. Each soldier is given a certain weight and depending on the previous iteration's success rate, their current position is dynamically modified. Comparing the recommended WSO to other metaheuristic techniques, it is faster and more competent at exploration and exploitation. The crucial component of our suggested WSO is choosing the best TDS estimates to reduce the operating duration of DOCRs with reference to reinforcement and hand-off setting limits. There are three cases discussed in this paper, and every case has its constraints derived, based on the time operation of relays and coordination criteria of relays.

The subsequent sections of this paper are structured as follows. Section 2 illustrates the DOCR problem formulation. In Section 3, the proposed WSO algorithm is described. Section 4 provides thorough explanations of the simulation findings for several multi-loop test frameworks. All simulation results using previous techniques are summarized in Section 5. Section 6 presents the findings.

2. DOCR Problem Formulation

Sensing the problem and rapidly detaching the afflicted portions is the main goal of DOCR coordination. The best TDS and PS parameters for each DOCR must be determined in order to accomplish this relay coordination objective. By meeting the various limitations outlined by the objective function (OF) (Equation (1)), the goal is to reduce the overall operating time of all major DOCRs, as follows:

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

where $T_{i,j}$ is the main relay's operating time for a malfunction in zone j. As a result, Equation (2) selects the following characteristic curve for the functioning relay R_i from a subset of the International Electrotechnical Commission (IEC) standard decisions, as follows:

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

For typical inverted type relays, the time dial setting (TDS), fault current (IF), plug setting (PS), and current transfer ratio (CTR) are denoted as TDS, IF, PS, and CTR, respectively. $\propto$ and k are constants with values of 0.14 and 0.02, respectively. Figure 1 illustrates the schematic diagram for the coordination of DOCRs in an electrical power network.

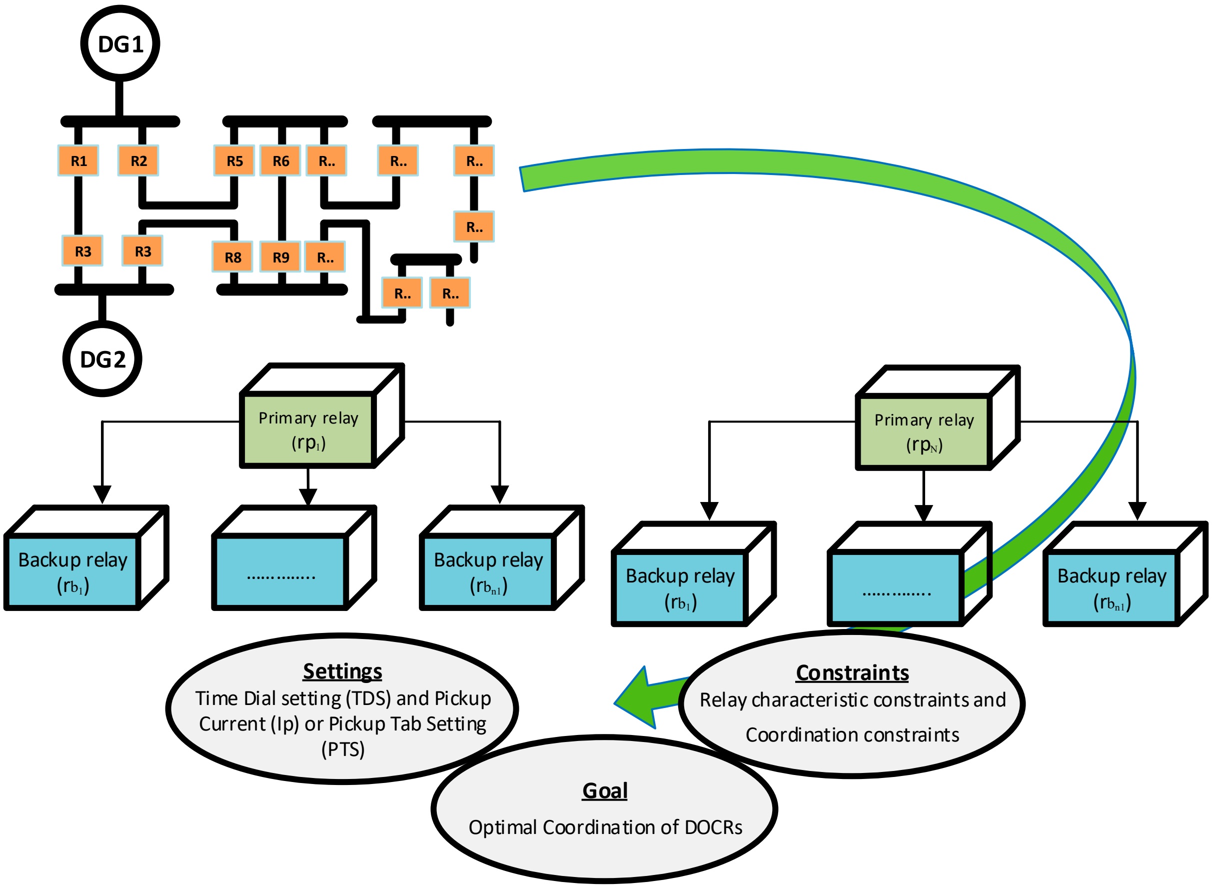

Figure 1. Coordinating DOCRs in a power grid.

2.1. Coordination Criteria

The main and backup protection scheme of an electrical protection system must be coordinated concurrently using a coordination time interval (CTI). Various conditions and causes may affect the CTI's value, which may range from 0.2 to 0.5 s. This can be expressed as follows:

$$T_b \geq T_p + CTI, \quad (3)$$

where T_p is the primary relay's operating time and T_b is the backup relay operating rb_1 time T_p.

2.2. Relay Setting Bounds

The criteria of relay restriction and coordination constraints may both be used to reduce the total working time. While alternative criteria are concerned with the synchronization of primary and backup relays, the main requirements specify the TDS and PS limitations. Relay constraints and design determine the ranges of the relay configuration parameters, which are represented as follows:

$$TDS_i^{min} \leq TDS_i^{max} \quad (4)$$

$$PS_i^{min} \leq PS_i \leq PS_i^{max}, \quad (5)$$

3. War Strategy Optimization Algorithm (WSO)

In order to protect themselves from the attacks of other dynasties, ancient kingdoms maintained an army. A diverse array of units constituted the kingdom's militia, including infantry, chariots, elephants, etc. Every kingdom in the conflict prepared a "Vyuha" assault against the other army. A Vyuha is a configuration or grouping of different army units used in battles to overthrow opposing kingdoms [47]. Every army's King and Commander-in-Chief directed the soldiers in a certain pattern so that it may achieve its goals. Based on the objective, risks, obstacles, and possibilities, a war plan was then developed. The military coordinated and engaged in combat with the adversary as part of a continuous, dynamic process known as a war strategy. This tactic may have been modified depending on the timing of events and the state of the battle. The King's and Commander's roles determined how the army soldier's status changes over time. All troops were able to see the flags that indicated the Commander's and the King's places, which were both prominently displayed. The team's warriors were taught to execute their tactics in accordance with the sounds of a drum or any other musical instrument. When a general passed away, a plan was created to inform the other generals of what to do, in order to reorganize and preserve the formulation of the war strategy. While an army man wanted to assault the other side and rise in rank, a King wanted to defeat the opposing leader.

3.1. The Following Is a Discussion of the Different Military Strategy Steps

3.1.1. Random Attack

To assault the enemy army, the army forces were dispersed equally and at random. The army general had a high assault force, making him the strongest member of the army. The King was in charge of several army generals.

3.1.2. Attack Strategy

Attacking the opponent was the main goal of this tactic. Command was assumed by the King, who issued orders to the army personnel. The vulnerable points of the opposition (promising search area) were identified by the army soldiers carrying out the assault. Two distinct chariots with flags on top were driven by the King and the Commander. Depending on where the King and the Commander were, the soldiers moved into a different location. A soldier's rank increased if he was successful in enhancing his assaulting force. The soldier reverted back to his original position if the new one was not combat-ready. At the beginning of the conflict, army units marched in all directions and made significant movements to alter their location.

3.1.3. Signaling Using Drums

Depending on the circumstances, the King issued directives to alter the plan. As a result, a squad of troops rhythmically pounded their drums. The troops therefore changed their tactics and altered their locations in accordance with the beat.

3.1.4. Defense Strategy

The protection of the King was the main goal of this tactic. With the aid of the army forces, the commander or army chief built a chain and surrounded the king. Each soldier adjusted their position in accordance with the locations of the soldiers around them and the King's posture. Throughout the fight, army personnel attempted to scour a sizable portion of the battlefield (search space). The army periodically adjusted its plan dynamically in an effort to confound the opposing army.

3.2. Mathematical Modeling of the War Strategy

Two military plans have been modeled. In the first scenario, each soldier adjusts his location based on the whereabouts of the King and Commander. In Figure 2, this attacking model is shown and discussed. The King positions himself well to launch a fierce assault on the resistance. The soldier with the greatest offensive force is thus regarded as the King. All troops will start the conflict with the same rank and weight. If the soldier successfully implements the plan, his rank rises. The ranks and weights of every soldier will, however, be adjusted as the fight goes on depending on how well the plan is executed. The King, Army chief, and troops stay in very close-quarters positions as the battle approaches its conclusion (Algorithm 1).

$$X_i(t+1) = X_i(t) + 2 \times \rho \times (C - K) + rand \times (W_i \times K - X_i(t)) \quad (6)$$

where $X_i(t+1)$ is a new position, X_i represents the previous position, C represents the position of the commander, K represents the position of the King, and W_i is the weight.

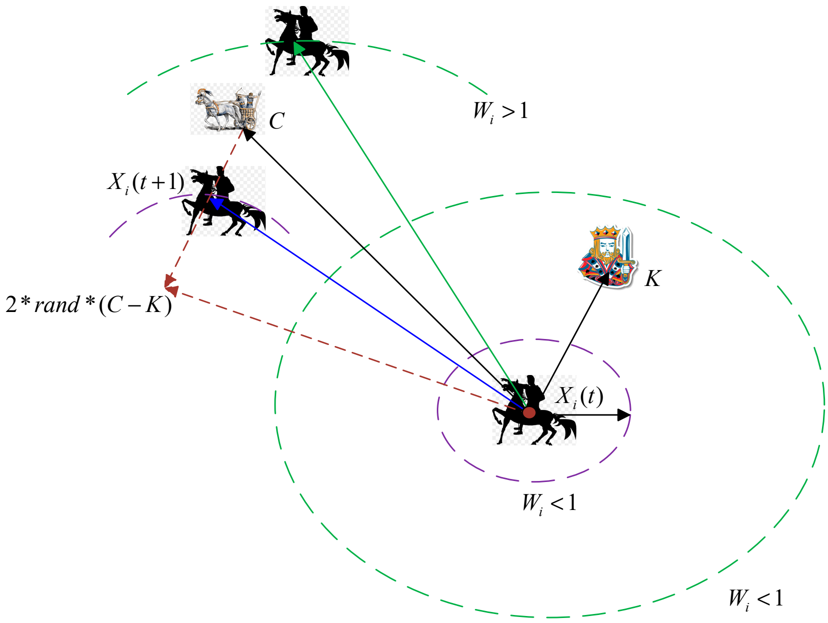

Figure 2. Attack strategy in WSO.

The soldier assumes the previous position if the attack force (fitness) at the new position F_n is lower than that of the prior position F_p, as follows:

$$X_i(t+1) = (X_i(t+1)) \times (F_n \geq F_p) + (X_i(t)) \times (F_n < F_p) \quad (7)$$

The rank R_i of the soldier will be raised if the position update is successful, as follows:

$$R_i = (R_i + 1) \times (F_n \geq F_p) + (R_i) \times (F_n < F_p) \quad (8)$$

According to the rank, the new weight is determined as follows:

$$W_i = W_i \times \left(1 - \frac{R_i}{Max\_iter}\right)^{\alpha} \quad (9)$$

α is an adjustable parameter wherein the locations of the King, the army commander, and a random soldier provide the basis for the second strategic position update. The updating of the ranking and weight, however, has not changed.

$$X_i(t+1) = X_i(t) + 2 \times \rho \times (K - X_{rand}(t)) + rand \times W_i \times (c - X_i(t)) \quad (10)$$

Figure 3 depicts the flowchart for the suggested war strategy optimization method. Each soldier is given a weight that is adaptable and varies from iteration to iteration. Soldiers with higher levels of fitness will weigh less, while those with lower levels of fitness will weigh more. At the beginning of the fight, every soldier moves with hefty steps as their weight fluctuates.

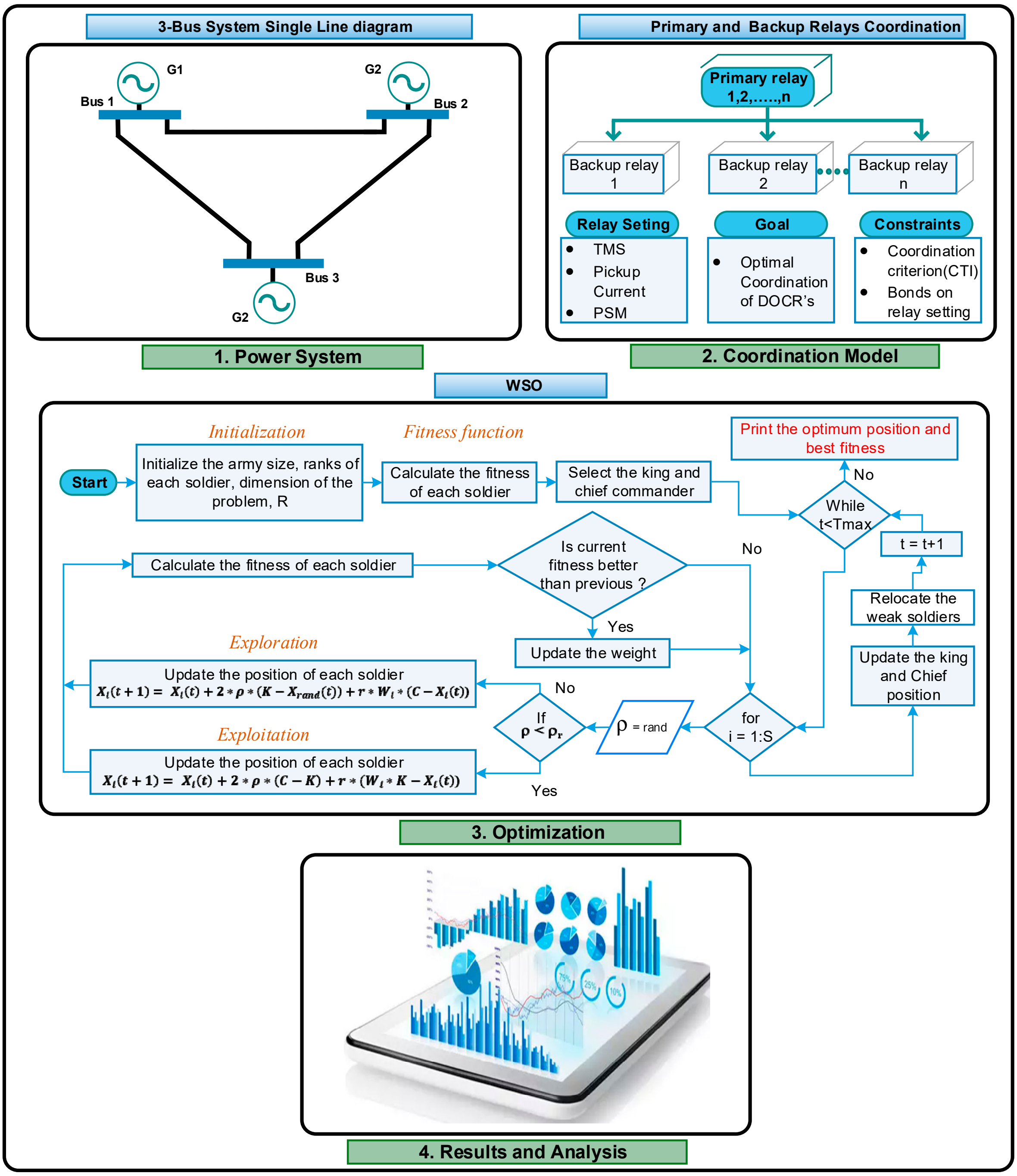

Figure 3. War strategy optimization algorithm's flow chart.

The troops move in little steps to achieve their destination as the fight nears its conclusion, and the weight fluctuates slightly. The troops do not precisely follow the King since the strategy choice is based on the random value, which causes them to proceed in a random path. This enhances the algorithm's capacity for exploration. The army forces locate the objective location at the conclusion of the conflict. The King and Commander are quite near to the objective, and army forces are encircling it as well. The whole troop travels in tiny increments and converges to the goal place as a result of Equations (6) and (10). As a result, we may conclude that the algorithm also has an exploitation characteristic.

3.3. Characteristics of the Suggested Algorithm

The weights, in contrast to the majority of algorithms, are adaptable and continually alter as the number of iterations changes. Based on his rank, every answer (soldier) has a distinct weight. Whether a soldier effectively increases his fitness during the updating stage determines whether the weight of that soldier is updated. There will be nonlinear variation in the weights. Early versions of the weights fluctuate in big increments, but final iterations vary in tiny amounts. The global optimal value is therefore attained sooner. Both exploration and exploitation are aspects of the suggested method. There are two steps to the position update procedure. This enhances the potential to discover the best solution. The suggested approach is straightforward and has a lower computational time.

Algorithm 1: Pseudocode of WSO for DOCR Coordination.

Step 1: Initialize parameters.
Set the population size, maximum number of iterations MaxIter, and convergence tolerance ϵ.
Define the parameter bounds for relay settings.
Initialize battle field dimensions representing the search space.
Step 2: Define the objective function—DOCR objective.
Minimize relay operating time for fault conditions.
Ensure coordination with other relays and penalize miscoordination to avoid malfunctions.
Step 3: Generate an initial population of warriors (solutions).
Randomly initialize warriors within the specified bounds for TMS.
Each warrior represents a potential solution for DOR settings.
Step 4: Evaluate the fitness of each warrior.
Calculate each warrior's fitness using the DOCR objective function.
Fitness measures the effectiveness of relay settings for accurate fault detection and coordination.
Step 5: Identify the best warrior, Best Warrior, with the highest fitness score.
Step 6: Set iteration counter.
Step 7: Begin optimization loop. While iteration < MaxIter and convergence criterion is not met:
For each warrior in the population:

1. **Attack maneuver:** Adjust the warrior's position based on the strategy of Best Warrior.
   Use a proximity factor to decide attack intensity:
   If the warrior is close to Best Warrior, fine-tune the position.
   If far, approach rapidly toward Best Warrior to explore new potential solutions.
2. **Retreat maneuver:** If the warrior is too far or has a low fitness score, retreat to explore a new position.
   Generate a new candidate solution within safe bounds for TMS.
3. **Reorganization maneuver:** Occasionally regroup warriors randomly around Best Warrior to maintain population diversity and prevent premature convergence.

Apply boundary constraints to keep each warrior's TMS values within the allowed range.
Recalculate the fitness of each warrior using the DOCR objective function.
Update Best Warrior if a warrior with a higher fitness is found.
Increment iteration counter.
Step 8: End the loop when the maximum number of iterations is reached or convergence is achieved.
Step 9: Output the results.
Return the DOCR settings (position of Best Warrior) for TMS.
Report DOCR coordination characteristics and expected operating times for different fault scenarios.

4. Results

For both single- and multi-loop distribution networks, the ideal value of the overcurrent relay (OCR) was found and the appropriate code was produced in the MATLAB software R2023b. The results showed that WSO provided the most adequate performance and the best efficiency across all case studies, regardless of the system type (single- or multi-loop). The reference lists [48–53] provide more information about each of the three case studies that were used. The following WSO parameters were utilized in all of the case studies:

Population size: 50

Number of iterations: 1000

All case studies exhibit an extensive definition of the problem solution and the application of WSO to identify the optimized solution.

5. Multi-Loop Parallel Distribution Power System

5.1. Case 1

This case discusses a power distribution system with four sites of failure and eight overcurrent protection relays in a single-ended multi-loop parallel design. Figure 4 shows four fault spots (A–D) and eight directional overcurrent relays (R1–R8). As a result of the fault current, the combined load current, including overload, is extremely small. For each of the four failure types, Table 1 shows the connection between the main and backup relays. The relays' current transformer (CT) to plug setting (PS) ratios can be seen in Table 2. There is a 0.2 s CTI and a 0.1 s minimum operating time (MOP) for every relay. The information about the current passing through the relays and the constant αp at various defective spots is given in Table 3.

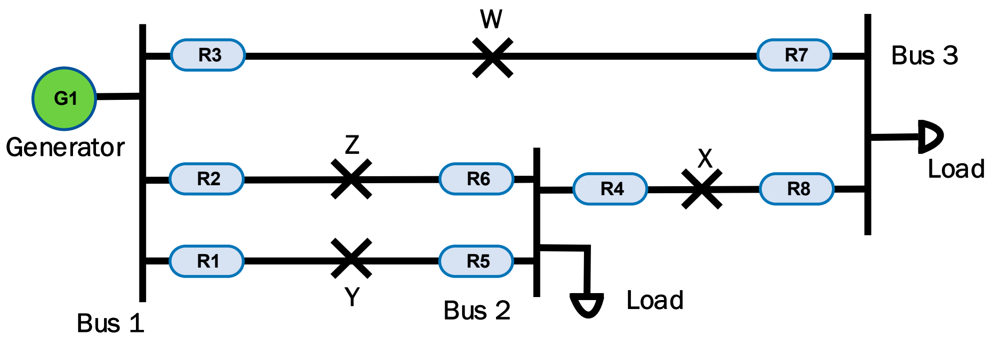

Figure 4. Power distribution system with a single end and multiple loops (Case 1).

Table 1. Primary relay relationships with backup relay (Case 1).

Fault Location	Primary Relay	Backup Relay
W	3, 7	--, 4
X	4, 8	(1, 2), 3
Y	1, 5	--, 8
Z	2, 6	--, 8

-- Indicates the absence of a backup relay.

Table 2. Parameters of the relays' plugs (PS) and their current transformer (CT) ratios (Case 1).

No. of Relays	Current Transformer (CT) Ratio	Plug Setting (PS)
R1	300:1	50%
R2	300:1	50%
R3	300:1	50%
R4	300:1	100%
R5	100:1	100%
R6	100:1	100%
R7	300:1	100%
R8	100:1	100%

Table 3. I_{relay} and α_p constant calculations (Case 1).

Fault Location		Relay							
		R1	R2	R3	R4	R5	R6	R7	R8
W	I_{relay}	0.731	0.731	3.655	1.462	--	--	1.462	-
	α_p	18.3606	18.3606	3.4494	18.3606	--	--	18.3606	-
X	I_{relay}	1.8275	1.8275	1.462	3.655	--	--	--	4.386
	α_p	5.3311	5.3311	6.4543	5.3311	--	--	--	4.6651
Y	I_{relay}	7.31	2.193	0.731	--	8.772	--	--	2.193
	α_p	2.5402	4.6651	18.3606	--	3.154	--	--	8.8443
Z	I_{relay}	2.193	7.31	0.731	--	--	8.772	--	2.193
	α_p	4.6651	2.5402	18.3606	--	--	3.154	--	8.8443

-- means no fault seen by the relay.

Here, eight constraints derive from the limitations of the relay operation and six constraints derive from the coordination condition, totaling fourteen constraints. The TMS range is from 0.025 to 1.1. y_1, y_2, y_3, y_4, y_5, y_6, y_7, and y_8 are the identification numbers for the eight relays that make up the TMS.

From Table 1, the *OF* can be derived as follows:

$$OF = 30.8970y_1 \quad +30.8970y_2 + 46.6249y_3 + 23.6917y_4 + 3.154y_5 + 3.154y_6 \\ +18.3606y_7 + 22.3537y_8 \tag{11}$$

The constraints derived from the relays are as follows:

$$2.5402y_1 \geq 0.1 \tag{12}$$

$$2.5402y_2 \geq 0.1 \tag{13}$$

$$3.4494y_3 \geq 0.1 \tag{14}$$

$$5.3311y_4 \geq 0.1 \tag{15}$$

$$3.154y_5 \geq 0.1 \tag{16}$$

$$3.154y_6 \geq 0.1 \tag{17}$$

$$18.3606y_7 \geq 0.1 \tag{18}$$

$$4.6651y_8 \geq 0.1 \tag{19}$$

None of the constraints described in (15), (18), and (19) were able to meet the minimal limit of 0.025, which is the TMS minimum value. The constraints can be adjusted in the following ways to fix the issue:

$$y_4 \geq 0.025 \tag{20}$$

$$y_7 \geq 0.025 \tag{21}$$

$$y_8 \geq 0.025 \tag{22}$$

All of the equations' constraints fall inside the TMS's minimal value. Consequently, the constraints that we achieve as a result of coordination are as follows:

$$18.3606y_4 - 18.3606y_7 \geq 0.2 \tag{23}$$

$$5.3311y_1 - 5.3311y_4 \geq 0.2 \tag{24}$$

$$5.3311y_2 - 5.3311y_4 \geq 0.2 \tag{25}$$

$$6.4543y_3 - 4.6651y_8 \geq 0.2 \tag{26}$$

$$8.8443y_8 - 3.154y_5 \geq 0.2 \quad (27)$$

$$8.8443y_8 - 3.154y_6 \geq 0.2 \quad (28)$$

In comparison to the SM approach, the suggested WSO method worked and performed better, as shown in Table 4. There was a problem with the SM method's random beginning solution, but the suggested algorithm fixed it. The best solution for each sub-carrier was found, minimizing the overall operating time ($\sum$Top). This also led to faster and better convergence of the over-current relay problem; the TMS solutions obtained after convergence satisfy all requirements shown in Figure 5. Figure 6 is a visual depiction of the net gain achieved by the proposed algorithm versus the SM and HPSO methods. Evidence of WSO's superiority and benefits over the other method was shown by comparing its results with those of a previously published algorithm [48]. The WSO results in Table 4 were derived from objective function (OF) and its constraints, using MATLAB simulations, which are also shown in Figure 5.

Table 4. Comparative analysis of optimized time multiplier setting (TMS) with other techniques (Case 1).

TMS	SM [49]	HPSO [33]	WSO
TMS (R1)	0.0734	0.0734	0.0734
TMS (R2)	0.0734	0.0734	0.0734
TMS (R3)	0.0555	0.0538	0.0538
TMS (R4)	0.0359	0.0359	0.0359
TMS (R5)	0.03171	0.025	0.0250
TMS (R6)	0.03171	0.025	0.0250
TMS (R7)	0.025	0.025	0.0250
TMS (R8)	0.03392	0.0315	0.0315
$T_{op}[OF(s)]$	9.3912	9.2155	9.2154

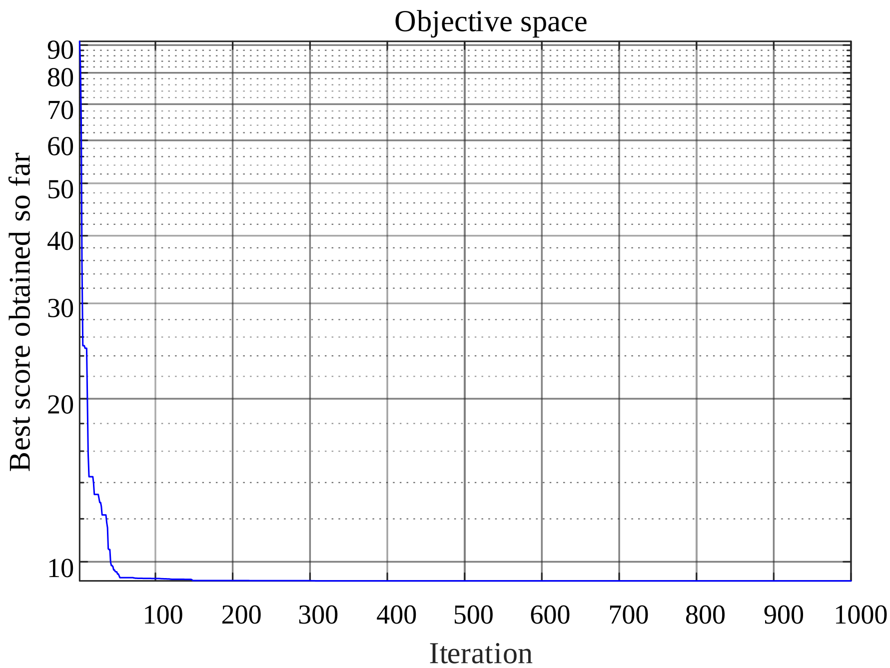

Figure 5. Convergence characteristic graph for Case 1.

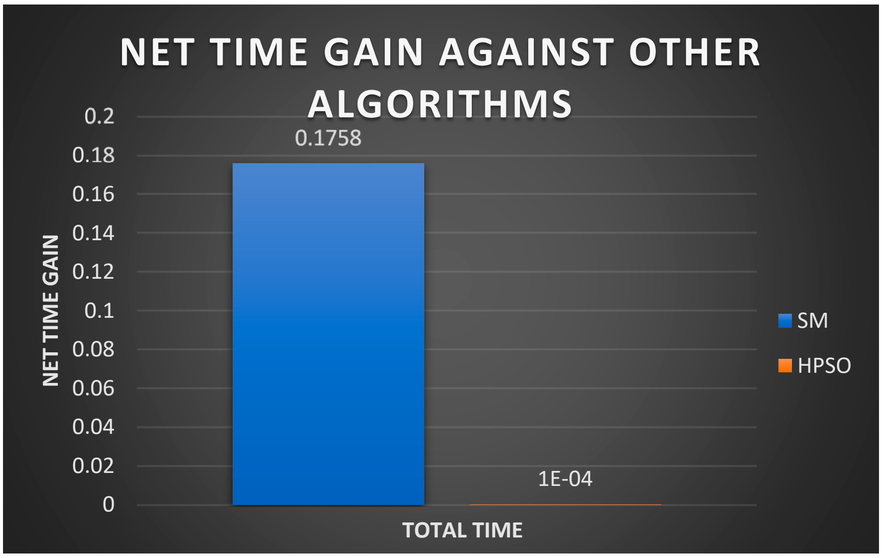

Figure 6. Analysis of WSO with other algorithms (for Case 1).

5.2. Case 2

This case discusses a multi-loop parallel power distribution system that has four sites of failure and six overcurrent protection relays. Figure 7 shows four failure locations (A–D) and six directional overcurrent relays (R1–R6). It is important to ensure that only relays R4 and R6 point towards the AC power source; the rest can be non-directional. Every relay has a 0.3 s CTI and a minimum operating time (MOP) of 0.1 s. To the right of each relay is the current transformer (CT) to plug setting (PS) ratio, as illustrated in Table 5. Primary and backup relays are related, as seen in Table 6. Table 7 provides the constant α_p and the currents observed by the relays (I_{relay}) for each fault point.

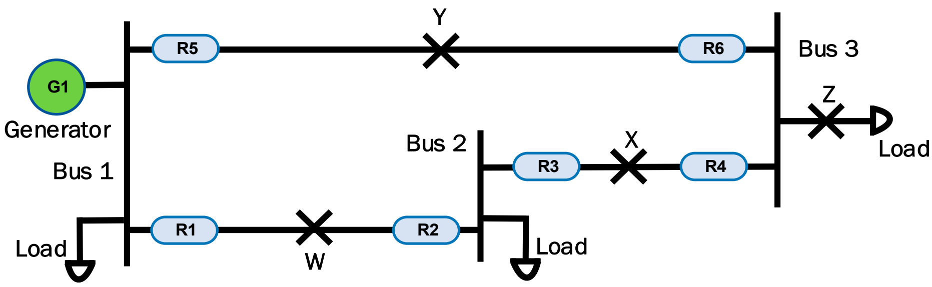

Figure 7. Power distribution system with a single end and multiple loops (Case 2).

Table 5. Parameters of the relays' plugs (PS) and their CT ratios (Case 2).

No. of Relays	Plug Setting	Current Transformer (CT) Ratio
R1	1	1000:1
R2	1	300:1
R3	1	1000:1
R4	1	600:1
R5	1	600:1
R6	1	600:1

Table 6. Primary and backup relays relationship (Case 2).

Fault Location	Primary Relay	Backup Relay
W	1, 2	--, 4
X	3, 4	1, 5
Y	5, 6	--, 3
Z	3, 5	1, --

-- means absence of backup relay.

Table 7. Calculations of I_{relay} and α_p constant (Case 2).

Faulty Location		Relay					
		R1	R2	R3	R4	R5	R6
W	I_{relay}	6.579	3.13	--	1.565	1.565	--
	α_p	3.646	6.065	--	15.55	15.55	--
X	I_{relay}	2.193	--	2.193	2.193	2.193	--
	α_p	8.844	--	8.844	8.844	8.844	--
Y	I_{relay}	1.096	--	1.096	--	5.482	1.827
	α_p	75.91	--	75.91	--	4.044	11.539
Z	I_{relay}	1.644	--	1.644	--	2.741	--
	α_p	13.99	--	13.99	--	6.872	--

-- means no fault seen by the relay.

Here, there are eleven constraints in total; six and five constraints are derived from the limits of the relay operation and from the coordination condition, respectively. The TMS range is from 0.025% to 1.1%. The TMS values for each relay are y_1, y_2, y_3, y_4, y_5, and y_6, in that order.

From Table 7, the OF can be derived as follows:

$$OF = 102.4y_1 + 6.06y_2 + 98.75y_3 + 24.4y_4 + 35.31y_5 + 11.53y_6 \tag{29}$$

The constraints obtained from the relays are given below:

$$3.646y_1 \geq 0.1 \tag{30}$$

$$6.055y_2 \geq 0.1 \tag{31}$$

$$8.844y_3 \geq 0.1 \tag{32}$$

$$8.844y_4 \geq 0.1 \tag{33}$$

$$4.044y_5 \geq 0.1 \tag{34}$$

$$11.539y_6 \geq 0.1 \tag{35}$$

Because TMS has a minimum limit of 0.025, the constraints of Equations (31)–(35) could not be satisfied. Hence, these limitations can be adjusted as follows:

$$y_2 \geq 0.025 \tag{36}$$

$$y_3 \geq 0.025 \tag{37}$$

$$y_4 \geq 0.025 \tag{38}$$

$$y_5 \geq 0.025 \tag{39}$$

$$y_6 \geq 0.025 \tag{40}$$

The constraints resulting from coordination condition are derived from Table 2 and are given below:

$$15.55y_4 - 6.065y_2 \geq 0.3 \quad (41)$$

$$8.844y_1 - 8.844y_3 \geq 0.3 \quad (42)$$

$$8.844y_5 - 8.844y_4 \geq 0.3 \quad (43)$$

$$75.91y_3 - 11.53y_6 \geq 0.3 \quad (44)$$

$$13.998y_1 - 13.998y_3 \geq 0.3 \quad (45)$$

According to Table 8, the suggested WSO method outperforms the other cutting-edge approaches. The proposed WSO outperforms competing metaheuristic algorithms in terms of exploration competency and speed, which in turn makes the WSO's population members more selective in their pursuit of the best solution. The simulated objective function (OF) with the computed constraints is shown in Figure 8, generated using MATLAB. The graphical representation of the total net gain achieved by comparing the CGA, FA, and CFA algorithms is illustrated in Figure 9. The net gain between CGA and WSO is 4.01 s, while, for FA and CFA, the net gains are 4.38 s and 2.52 s, respectively, for the WSO. Based on these comparison results, the WSO algorithm demonstrates superior performance and offers more advantages over CGA, FA, CFA, and CPSO.

Table 8. Comparative analysis of the optimized time multiplier setting(TMS) with other techniques (Case 2).

TMS	CFA [50]	FA [50]	CGA [51]	CPSO [52]	HPSO [33]	WSO
TMS (R1)	0.027	0.027	0.0765	0.0589	0.0588	0.0589
TMS (R2)	0.221	0.13	0.034	0.0250	0.0249	0.0250
TMS (R3)	0.025	0.025	0.0339	0.0250	0.0251	0.0250
TMS (R4)	0.025	0.025	0.036	0.0290	0.0289	0.0290
TMS (R5)	0.363	0.489	0.0711	0.0630	0.0629	0.0630
TMS (R6)	0.029	0.0285	0.0294	0.0250	0.0251	0.0250
$T_{op}(s)$	14.39	16.25	15.88	11.87	11.86	11.87

-- means absence of backup relay.

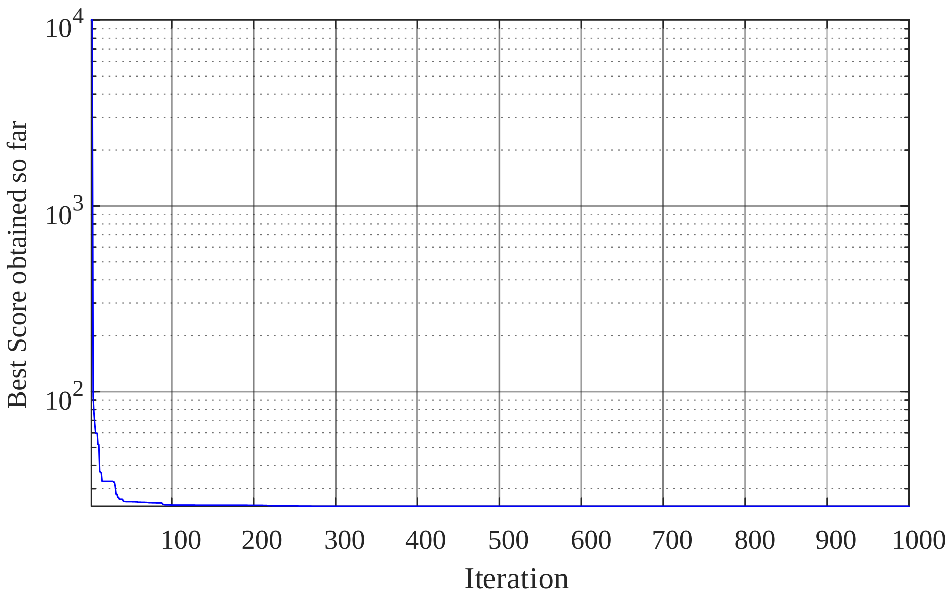

Figure 8. Convergence characteristic graph for Case 2.

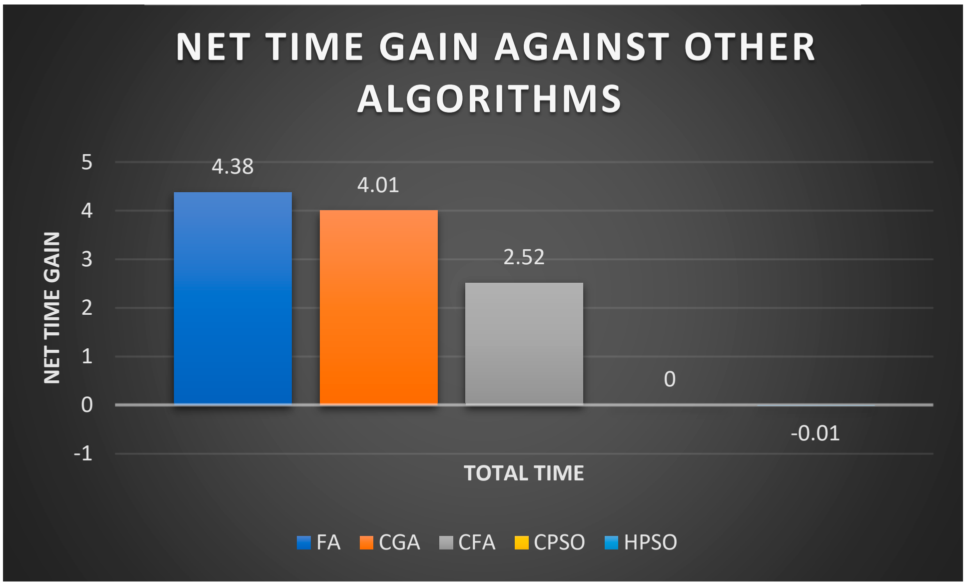

Figure 9. Comparison analysis of WSO with other algorithms (for Case 2).

5.3. Case 3

Case 3 involves an eight-over current relay multi-loop system, as seen in Figure 10. The placement of fault currents in various feeders dictates a unique configuration and combination of primary and backup pairs in the model. There are six different areas of failure that are highlighted. The six fault foci's aggregate fault current and the relay's important reinforcement relationship are listed in Table 9. The recommended settings for all relays are a plug setting of one and a CT percentage of 100:1, as given in Table 10. While Table 11 provides the constant α_p and the currents observed by the relays (I_{relay}) for each fault point.

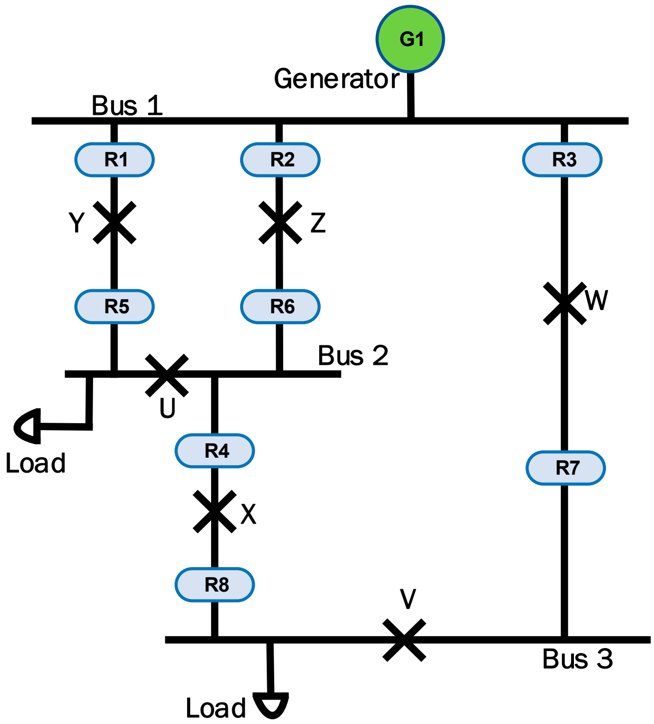

Figure 10. Power distribution system with a single end and multiple loops (Case 3).

Table 9. Relays' primary/backup relationships and total fault current (Case 3).

Fault Location	Total Fault Current	Primary Relay	Backup Relay
U	2330	1, 2, 8	--, --, 3
V	1200	3, 4	--, 1, 2
W	1400	3, 7	--, 4
X	1400	4, 8	1, 2, 3
Y	2800	1, 5	--, 8
Z	2800	2, 6	--, 8

-- means absence of backup relay.

Table 10. Parameters of the relays' plugs (PS) and their CT ratios (Case 3).

No. of Relays	Plug Setting	Current Transformer (CT) Ratio
R1	1	100:1
R2	1	100:1
R3	1	100:1
R4	1	100:1
R5	1	100:1
R6	1	100:1
R7	1	100:1
R8	1	100:1

Table 11. a_ρ Constants and relay currents for Case 3.

Fault Location		Relay							
		R1	R2	R3	R4	R5	R6	R7	R8
U	I_{relay}	10	10	3.3	--	--	--	--	3.3
	a_ρ	2.971	2.971	5.749	--	--	--	--	5.749
V	I_{relay}	3.45	3.45	5.1	6.9	--	--	--	--
	a_ρ	5.584	5.584	4.227	3.551	--	--	--	--
W	I_{relay}	2	2	10	4	--	--	4	--
	a_ρ	10.035	10.035	2.971	4.9804	--	--	4.9804	--
X	I_{relay}	5	5	4	10	--	--	--	4
	a_ρ	4.281	4.281	4.9804	2.971	--	--	--	4.9804
Y	I_{relay}	20	6	2	--	8	--	--	2
	a_ρ	2.267	3.837	10.035	--	3.297	--	-	10.035
Z	I_{relay}	6	20	2	--	--	8	--	2
	a_ρ	3.837	2.267	10.035	--	--	3.297	--	10.035

-- means no fault seen by the relay.

Here, there are eight constraints imposed by coordination criteria, eight limitations imposed by limits on the working time of the relays (or their TMS), and eight variables representing the TMS of eight relays. There will be eight restrictions and seventeen variables in the inverse of the problem. However, in this case, eight conditions are considered as coordination criteria, in order to validate and ensure the efficiency of WSO by taking the value of CTI as 0.6 s, and the minimum operating time of relay as 0.1 s. The TMSs of all eight relays are y_1–y_8.

The optimization problem can be depicted as follows:

$$minz = 28.975y_1 \quad +28.975y_2 + 37.736y_3 + 11.502y_4 + 3.297y_5 + 3.297y_6 \\ +4.9807y_7 + 30.7994y_8 \tag{46}$$

The constraints arising from the relays' minimum operating time (MOT) are as follows:

$$2.971y_1 \geq 0.1 \tag{47}$$

$$2.971y_2 \geq 0.1 \tag{48}$$

$$5.584y_3 \geq 0.1 \tag{49}$$

$$4.980y_4 \geq 0.1 \tag{50}$$

$$3.297y_5 \geq 0.1 \tag{51}$$

$$3.297y_6 \geq 0.1 \tag{52}$$

$$4.980y_7 \geq 0.1 \tag{53}$$

$$10.035y_8 \geq 0.1 \tag{54}$$

The constraints resulting from the coordination of relays with CTI, which is assumed to be 0.6, are as follows:

$$5.749y_3 - 5.749y_8 \geq 0.6 \tag{55}$$

$$5.584y_1 - 3.551y_4 \geq 0.6 \tag{56}$$

$$5.584y_2 - 3.551y_4 \geq 0.6 \tag{57}$$

$$4.980y_4 - 4.980y_7 \geq 0.6 \tag{58}$$

$$4.281y_1 - 2.971y_4 \geq 0.6 \tag{59}$$

$$4.980y_3 - 4.980y_8 \geq 0.6 \tag{60}$$

$$10.035y_8 - 3.297y_5 \geq 0.6 \tag{61}$$

$$10.035y_8 - 3.297y_6 \geq 0.6 \tag{62}$$

Identical factors to those described in case study 1 are used to evaluate the objective function using the proposed WSO algorithm. Table 12 shows that the TMS and total operational time are optimized, with the optimal estimates of the acquired TMS. It is certain that the OCRs will keep working together and operate at any proportional possible period for a fault in the network because of the results shown in Table 12. Obtaining the optimal solution with fewer iterations and faster convergence is demonstrated in Figure 11, which shows the objective function obtained during the simulation for the top candidate solution in each iteration. Every one of the optimal values found by WSO is in full compliance with all of the coordination requirements. Table 12 displays the results obtained by the genetic, RTO, and JAYA algorithms, respectively, while the results obtained by the WSO computations are contrasted. WSO achieves an optimal TMS and overall time gain values that are 7.7 s faster than GA and 2.57 s faster than RTO, respectively, compared to the other two algorithms. The graphical representation of the total net gain achieved by comparing the GA, RTO, and JAYA algorithms is illustrated in Figure 12. The net gain between GA and WSO is 7.7784 s, while, for RTO and JAYA, the net gains are 2.5764 s and 0.8484s s, respectively, for the WSO

Table 12. Optimal TMS value.

TMS	RTO [48]	GA [53]	JAYA [35]	WSO
TMS (R1)	0.02521	0.2975	0.2412	0.2411
TMS (R2)	0.02521	0.2975	0.2412	0.2000
TMS (R3)	0.2000	0.2270	0.1903	0.1902
TMS (R4)	0.1510	0.1730	0.1455	0.1455
TMS (R5)	0.0303	0.0607	0.0303	0.0303
TMS (R6)	0.0303	0.0607	0.0303	0.0303
TMS (R7)	0.0250	0.0402	0.0250	0.0250
TMS (R8)	0.0800	0.1129	0.0698	0.0697
$T_{op}(s)$	26.681	31.883	24.953	24.1046

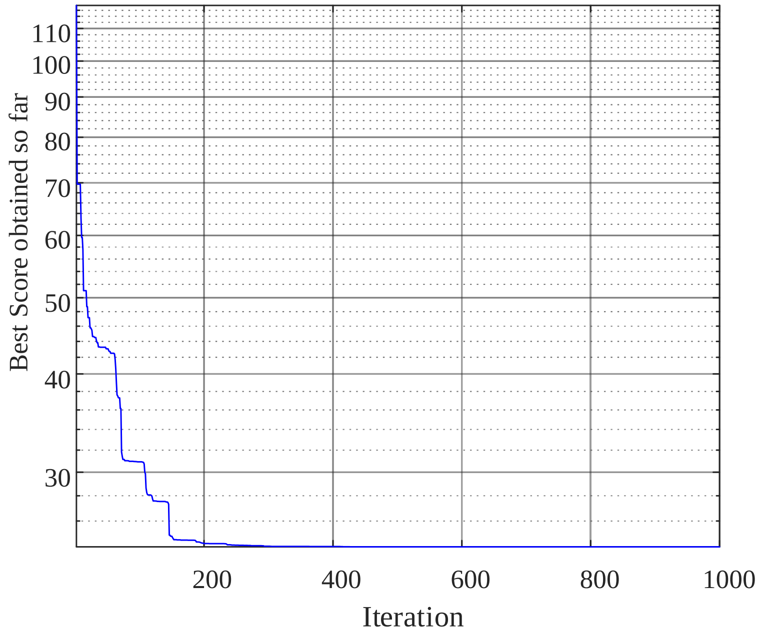

Figure 11. Convergence characteristic graph for Case 3.

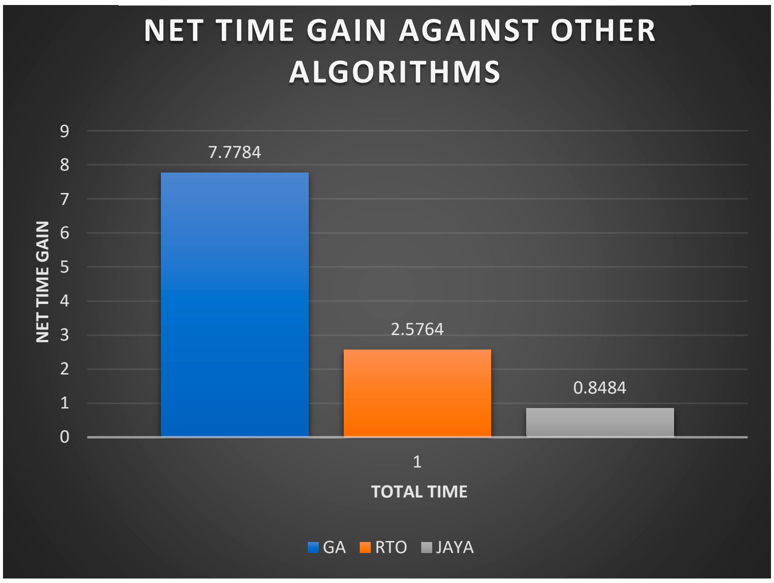

Figure 12. Comparison analysis of WSO with other algorithms (Case 3).

Considering how tiny the system is, this total time gain is more than enough. The WSO has consistently shown remarkable performance in reducing total operational time to an optimal value and will also ensure proper coordination in the event of a malfunction. On top of that, WSO uses less processing and running time to achieve the best answer. Every time, the value that WSO obtains for all the OCRs will be enough to satisfy the coordination restrictions. In addition, the coordination limitations have not been proven to be desecrated.

6. Conclusions

In order to properly assess the limitations of different DOCR models, this work suggests the WSO algorithm. The effectiveness of the WSO is tested by analyzing these models' parameter identification difficulties. By drastically cutting overall operation time, WSO performs better in simulations than competing strategies found in the literature. Using the WSO method, we are able to reduce runtime for all three models. Both multi-loop and single power distribution systems are used to validate its performance, proving that it is better than other competing algorithms. All three scenarios' simulation results show that WSO effectively solves the constraint identification issues in DOCR models. The WSO can be hybridized with other nature-inspired optimization algorithms to enhance convergence rates and reduce computational complexity. Incorporating fractal fraction mathematics to modify the search and attack strategies can further improve performance. Future testing should involve higher bus systems under various scenarios to evaluate scalability. This method holds potential for real-time applications in addressing DOCR problems in future research.

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