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Overcurrent Relays Optimization in Distribution Networks Using Bald Eagle Search Algorithm

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Abstract

Efficient coordination of directional overcurrent relays (DOCRs) is a crucial aspect of any protection plan design. This involves selecting appropriate parameters, such as Time Dial Setting (TDS) and Plug Setting (PS) or Pick-up current (Ip), through an optimization approach to minimize the total tripping time of directional overcurrent protection relays positioned at a specific location. In this study, we introduce the Bald Eagle Search Optimizer (BES), a novel optimization method tailored for enhancing the coordination of directional overcurrent relays. Five systems were modeled and simulated to evaluate the efficacy of the proposed approach. The BES method leverages linear programming (LP), nonlinear programming (NLP), and mixed-integer nonlinear programming (MINLP) to optimize the TDS and PS while adhering to all constraints. Extensive evaluation using diverse benchmarks with varying topologies confirms the efficiency and robustness of the BES method, namely IEEE 3-bus (with and without distributed generation), IEEE 6-bus, and IEEE 8-bus systems, surpassing the performance of other algorithms documented in the literature under comparable conditions, ensuring equitable comparisons.

Keywords: bald eagle search, optimization, overcurrent relays, optimal coordination, relays settings.

1 Introduction

The directional relay protection system is designed to detect faults and isolate faulty regions from healthy sections of the network, aiming to minimize the impact of faults and maintain continuous service. If a fault occurs, the nearest primary relays should promptly address the issue. If these primary relays fail to respond for any reason, their backup relays must take over and complete the task. Coordinating Directional Overcurrent Relays (DOCRs) is a crucial aspect in the design of protection systems. DOCRs find application in various systems like multi-loop systems, ring feed systems, double-end fed feed systems, and single-end fed feed systems with parallel power supplies. They can also function as main

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relays in networked sub-transmission and distribution systems, as well as serve as local backup relays in transmission systems [1].

To address the coordination problem of DOCRs, several modern metaheuristic methodologies have been employed. For instance, the Firefly Algorithm (FA) and Improved Firefly Algorithm (IFA) were employed in [1], while the Seeker Algorithm (SA) was applied in [2]. Additionally, the Harris Hawks Optimizer (HHO) and JAYA were compared in [3], and the Teaching Learning-Based Optimization (TLBO) was investigated in [4]. Other optimization techniques include the Modified Teaching Learning-Based Optimization [5], the Biogeography-Based Optimization (BBO) and BBO-LP [6], as well as the Particle Swarm Optimization (PSO) used in [7, 8]. An artificial bee colony (ABC) and a hybrid ABC-PSO were employed in [9]. A Hybrid PSO-DE and Genetic Algorithm (GA) were applied in [10], and Hybrid GA-NLP approaches were used respectively in [11–13]. Furthermore, the Gray Wolf Optimizer (GWO) and Enhanced Gray Wolf Optimizer (EGWO) were developed in [14], while the electromagnetic field optimization algorithm (EFO) and its modified version (MEFO) were proposed in [15]. The Water Cycle Algorithm (WCA) was applied in [16], and a hybrid Cuckoo Search Algorithm (CSA) and Firefly Algorithm (FFA) were combined in [17]. An optimized adaptive protection scheme using Harris Hawk Optimization (HHO) for numerical and directional overcurrent relay coordination was presented in [18], an adaptive fuzzy directional Bat Algorithm (BA) [19]. Additionally, a hybrid GA-IPM method considering mixed time-current characteristic curves for DOCR coordination has been developed [20]. A comprehensive review of optimization techniques for directional overcurrent relay coordination is presented in [21]. Recently, the Intensified Goshawk Optimization Algorithm has been proposed to solve various optimization problems [22]. In addition, the hybridization of Particle Swarm Optimization (PSO) has been applied for optimal coordination of directional overcurrent protection relays in IEEE bus systems [23]. The novel application of Fractional Order Derivative Moth Flame Optimization Algorithm has shown promise in this regard [24]. Some other works have shown the efficiency of an improved Grey Wolf Optimizer [25]. On the other hand, B.H. Hamad and M.T. Alkhayyat have studied this concept for the coordination of relays with distributed generators [26]. Other notable improvements include the combination of Firefly Algorithm with linear programming [27], the application of a modified PSO for optimizing relay time dial settings [28]. These developments together enhance the robustness and efficiency of protection schemes in modern power systems. This research focuses on investigating the optimal relay configuration values and addresses the coordination problem between primary and backup relays using an optimization technique called Bald Eagle Search (BES). The study aims to improve the total operating time for each protection relay in various modeled and simulated cases, such as IEEE 6-bus, IEEE 8-bus, IEEE 3-bus, and IEEE 3-bus with distributed generation (DG). Three types of optimization formulations are used: linear programming (LP) as in [1], mixed integer nonlinear programming (MINLP) [3], and nonlinear programming (NLP) [9]. The choice of formulation depends on the nature of the variables, such as time dial setting (TDS), plug setting (PS), or pick-up current (Ip) design, to evaluate the effectiveness of the proposed algorithm.

In this article, the Bald Eagle Search Algorithm (BES) is compared with other algorithms mentioned in the literature, all of which employ various topologies. While Alsattar et al. [29] introduced the BES algorithm, its application in the field of optimal coordination of overcurrent relays is yet to be explored.

The selection of the Bald Eagle Search (BES) algorithm for this specific engineering problem is motivated by its robust mathematical framework, which effectively balances exploration and exploitation phases. Unlike traditional metaheuristics such as Particle Swarm Optimization (PSO) or Genetic Algorithms (GA) that often suffer from premature convergence in highly constrained, non-convex search spaces like the DOCR coordination problem, BES utilizes a unique three-stage hunting strategy (select space, search in space, swoop). This allows it to dynamically escape local optima without requiring an excessive number of complex internal control parameters to be tuned. Furthermore, while previous literature has explored various metaheuristics for DOCRs, the application of BES—specifically its rigorous performance assessment under strict computational fairness across LP, NLP, and MINLP formulations-represents a novel contribution that demonstrates superior scalability and robustness.

2 Problem Formulation

2.1 Objective function

It should be noted that while this optimization formulation focuses on the determination of TDS and PS/I_p settings, it operates under the assumption that the forward/reverse fault discrimination and directional element settings have been pre-configured by the fundamental directional protection logic of the relays. The objective herein is exclusively the optimal coordination of these pre-discriminated operating times.

In coordination studies, the summation of all primary relays operating time can be considered as an objective function that should be minimized. Therefore, the objective function can be expressed by (1) [29],

$$OF = \min \sum_{i=1}^{n} \omega_i \, OT_i, \tag{1}$$

where n is the total number of relays, ω_i stands for weight depending upon the probability of occurrence of a certain defect in the protection zone, which is usually set to 1, and OT_i is the i-th primary relay operation time calculated using (2) by three kinds of formulations:

$$OT_i = \left(\frac{c}{PSM_i^{b-a}} + d \right) \cdot TDS_i, \tag{2}$$

- LP: Linear Programming, where the operation time (OT) is a linear expression related with the time dial setting (TDS) for a predetermined constant value of pick-up current (I_p).
- NLP: Non-Linear Programming, where the design variables are TDS and I_p, in which I_p takes continuous variables.
- MINLP: Mixed Integer Non-Linear Programming, where the design variables are TDS and the plug setting (PS).

where PSM is the plug setting multiplier in (3), I_F is the fault current, PS and CT stand for the plug setting and the current transformer ratio of a relay R_i, respectively. a, b, c and d are constants relating to the relay's characteristics (inverse, very inverse, extremely inverse, etc.). Its values for a standard overcurrent relay are set by the ANSI/IEEE and IEC Standards as follows: $a = 1$, $b = 0.02$, $c = 0.14$, $d = 0$,

$$PSM_i = \frac{I_{Fi}}{I_{Pi}} = \frac{I_{Fi}}{PS_i \cdot CT_i}. \tag{3}$$

2.2 Constraints

The total trip time must be obtained by adhering to the following constraints:

Coordination criteria

$$OT_{sj} - OT_{pi} \geq CTI \tag{4}$$

where OT_{pi} is the operating time of the primary relay R_i, OT_{sj} is the operating time of the secondary relay R_j, and CTI is the coordination time interval. Equation (4) indicates that the minimum time between the primary and secondary relay must be confirmed during the optimization procedure. CTI usually takes values between 0.2 s and 0.5 s.

Relays operating time

The operating time constraints are given as:

$$OT_{i,\min} \leq OT_i \leq OT_{i,\max} \tag{5}$$

where $OT_{i,\min}$ and $OT_{i,\max}$ are the minimum and maximum value of operation time for i-th relay, respectively.

Time Dial and Pick-up Current Settings

When the fault current equals or exceeds the relay current setting (I_p), the TDS updates the time delay before the relay works. The bounds on TDS and I_p or PS are defined as:

$$TDS_{i,\min} \leq TDS_i \leq TDS_{i,\max} \tag{6}$$

$$I_{pi,\min} \leq I_{pi} \leq I_{pi,\max} \tag{7}$$

$$PS_{i,\min} \leq PS_i \leq PS_{i,\max} \tag{8}$$

Relays characteristics

Table 1 is used to choose the constant parameters of (2).

Table 1. Inverse Time Characteristics for DOCRs [30].

Curve description		a	b	c	d
Standard Inverse	IEC	1	0.02	0.14	0
Very Inverse	IEC	1	1.0	13.5	0
Extremely Inverse	IEC	1	2.0	80.0	0
Long Time Inverse	IEC	1	1	120	0

Penalty method

Because certain solutions may have an infeasible tripping time, a penalty term is added into the objective function (OF) as in (9), to ensure that the relay tripping time is greater than or equal to the specific value

$OT_{\min}$, and to prevent any violations of coordination constraints [30].

$$OF = \sum_{i=1}^{n} OT_{p_i} + \sum_{k=1}^{m} \text{penalty}(k), \tag{9}$$

where n is the number of relays, m is the number of relay pairs (Primary/Secondary (P/S)), and penalty(k) is expressed by (10)

$$\text{penalty}(k) = \begin{cases} \gamma \cdot |CTI - \Delta OT_k|, & \text{if } \Delta OT_k < CTI \\ 0, & \text{if } \Delta OT_k \geq CTI \end{cases} \tag{10}$$

with

$$\Delta OT_k = OT_{s_k} - OT_{p_k} \tag{11}$$

where γ represents the penalty coefficient. In this study, to ensure a severe penalty for constraint violations and to heavily bias the search towards feasible regions, the numerical value of γ is empirically set to 10^4.

3 The Bald Eagle Search Algorithm

The proposed BES algorithm is a nature-inspired metaheuristic optimization algorithm that emulates the hunting behaviour of bald eagles. The hunting strategy can be divided into three stages, namely: selecting space, searching within the selected space, and swooping, as shown in Figure 1.

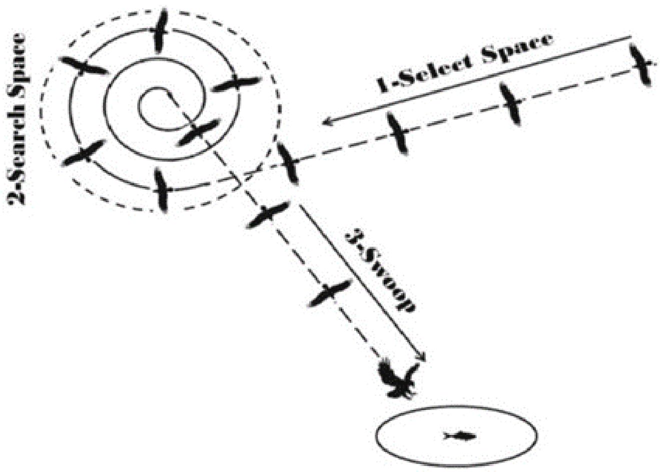

Figure 1. The three main stages of the hunting strategy in BES [29].

3.1 First Stage

In the selecting stage, bald eagles identify and select the best space with the large amount of food where they can hunt. This behaviour is presented mathematically by Equation (12) below [29],

$$P_{i,\text{new}} = P_{\text{best}} + \alpha \cdot r \cdot (P_{\text{mean}} - P_i), \tag{12}$$

where α is the control parameter for position changes, its value is between 1.5 and 2, r is a random number whose value is between 0 and 1, P_{mean} shows that these eagles have consumed all of the preceding points' information, and the new and current search spaces are denoted by P_{new} and P_{best}, respectively.

3.2 Second Stage

During the search stage, bald eagles look for prey within the chosen search space and move in different directions within a spiral space to speed up their search. The Equation (13) expresses the search movement mathematically as follows [29]:

$$P_{i,\text{new}} = P_i + y(i) \cdot (P_i - P_{i+1}) + x(i) \cdot (P_i - P_{\text{mean}}) \tag{13}$$

$$x(i) = \frac{x_r(i)}{\max(|x_r|)}, \quad y(i) = \frac{y_r(i)}{\max(|y_r|)} \tag{14}$$

$$x_r(i) = r(i) \cdot \sin(\theta(i)), \quad y_r(i) = r(i) \cdot \cos(\theta(i)) \tag{15}$$

$$r(i) = \theta(i) + R \cdot \text{rand} \tag{16}$$
$$\theta(i) = a \cdot \pi \cdot \text{rand}$$

where a is a parameter with a value between 5 and 10 to determine the corner between point search in the center point, and R is a parameter with a value between 0.5 and 2 to determine the number of search cycles.

3.3 Third Stage

The swooping stage where bald eagles swoop from the best location in the search space to their prey, all points advance towards the best point as well. This behavior is mathematically as indicated in (17) below [29],

$$P_{i,\text{new}} = \text{rand} \cdot P_{\text{best}} + x_1(i) \cdot (P_i - c_1 \cdot P_{\text{mean}}) + y_1(i) \cdot (P_i - c_2 \cdot P_{\text{best}}) \tag{17}$$

where $c_1, c_2 \in [1, 2]$.

With

$$x_1(i) = \frac{x_r(i)}{\max(|x_r|)}, \quad y_1(i) = \frac{y_r(i)}{\max(|y_r|)} \tag{18}$$

$$x_r(i) = r(i) \cdot \sinh[\theta(i)], \quad y_r(i) = r(i) \cdot \cosh[\theta(i)] \tag{19}$$

$$\theta(i) = a \cdot \pi \cdot \text{rand} \tag{20}$$

$$r(i) = \theta(i) \tag{21}$$

The whole bald eagle search mechanism is illustrated in Figure 2.

To further contextualize the proposed approach, recent advances in relay protection optimization are also noted, including the Whale Optimization Algorithm (WOA) for optimal DOCR coordination [31], adaptive protection of networked microgrids using relays with multiple setting groups [32], and optimal coordination of directional overcurrent and distance relays using various optimization algorithms [33].

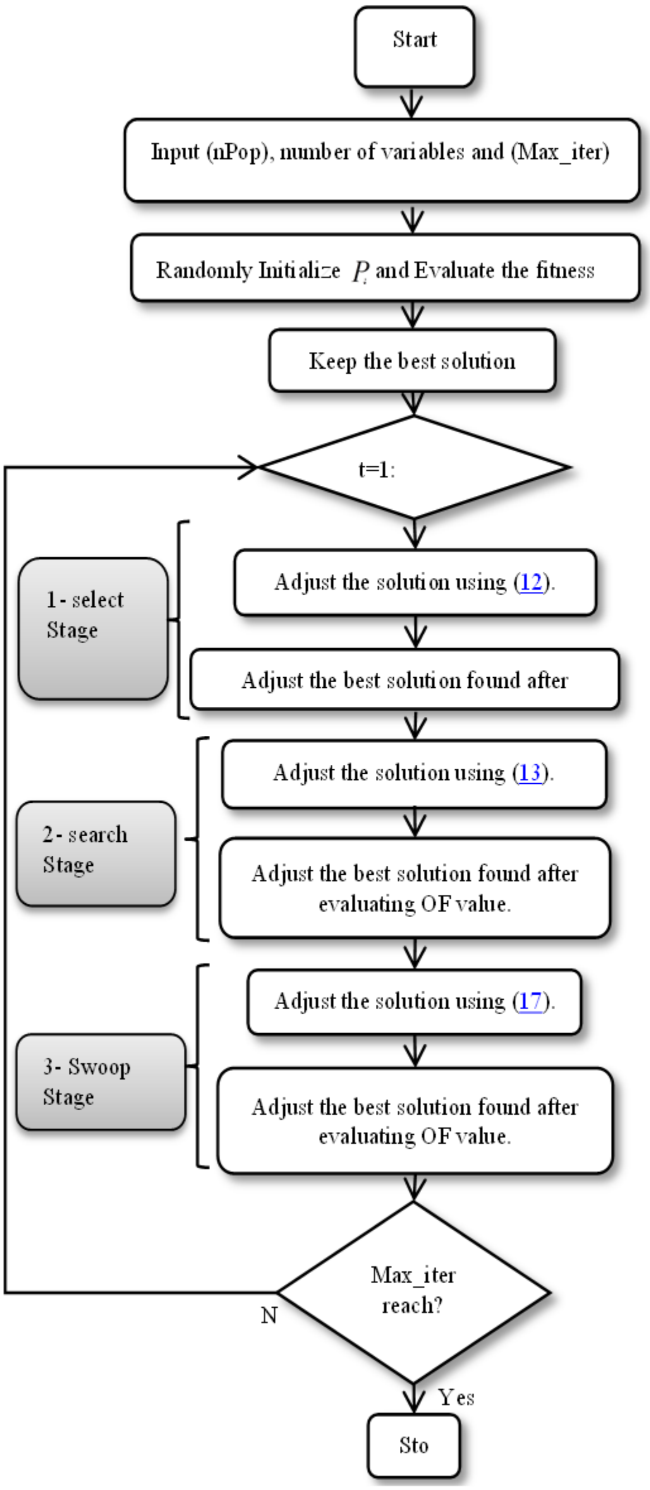

Figure 2. Flowchart illustrating the whole BES algorithm.

4 Test Result and Discussion

4.1 Settings

To ensure a rigorous and fair comparative assessment, all benchmark metaheuristic algorithms were evaluated under an identical computational budget. Specifically, the population size (N) was uniformly set to 50, and the maximum number of iterations ($T_{\max}$) was set to 1000 for all algorithms, ensuring an equal number of objective function evaluations. The hyperparameter tuning for the BES algorithm, as well as the competing algorithms, was conducted through a systematic trial-and-error procedure combined with guidelines from their respective foundational literature. For BES, the control parameter for changes in position (α) and the parameter controlling the search cycle (a) were set for each case study. Other algorithm-specific parameters (e.g., inertia weights in PSO, crossover rates in GA) were adopted from established optimal ranges in the literature and fine-tuned for this specific DOCR problem to prevent any favorable bias towards BES. Furthermore, to account for the stochastic nature of these optimizers, random seed initialization was controlled, and all algorithms were subjected to the same stopping criteria: reaching the maximum iteration limit or achieving a tolerance of 10^{-6} in objective function improvement.

4.2 Test Scenarios

In this study, the BES is examined in five different test scenarios. For relay coordination, the 6-bus system uses the linear programming optimization (LP) model, where the TDS is the only variable that can be optimized while keeping the PS value constant, necessitating the need for baseline PS values. The second test case, an 8-bus system, makes use of nonlinear programming (NLP), using TDS and I_p as design variables, the latter of which accepts continuous values. The 3-bus system shows the formulation in the third test case, which is continuous non-linear or mixed-integer nonlinear programming (MINLP), with TDS and PS as the variables that need to be optimized. The fourth test case optimizes a 3-bus system both without DG and with DG. The difference between the two formulations is that PS accepts discrete values in MINLP, whereas it accepts continuous values in NLP. In the test cases, the outcomes are compared to a range of algorithms, including PSO, PSO-DE, ABC, ABC-PSO, SBB, FA, IFA, Seeker, BBO, BBO-LP, HHO, JAYA, TLBO, and GA-LP. Using the MATLAB version R2016a, the simulation is run on a Windows 7 system with 12 GB of RAM and a Core (TM) 2.5 GHz processor.

4.3 Case 1: IEEE 6-Bus Test Case

The bald eagle's method is evaluated and validated on the 6-bus [1], system depicted in Figure 3, for the first example using LP formulation.

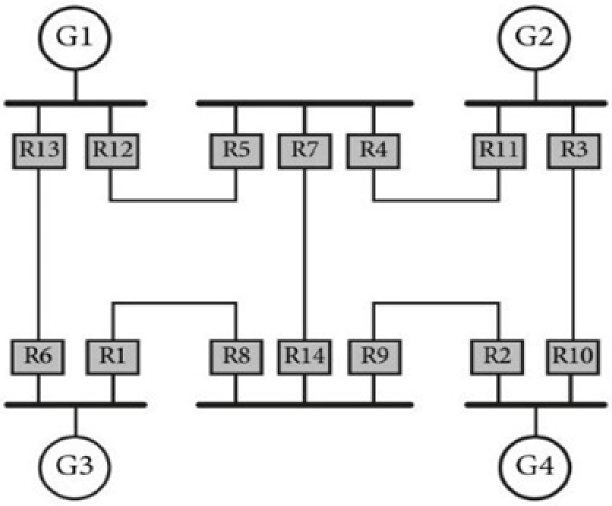

Figure 3. IEEE 6-bus DOCRs coordination problem model [1].

The six-bus system, which has seven lines, four generators, and 14 DOCRs, is shown in Figure 3 as a single line diagram. The data cited in [1], presents the system information for the three faults on each line, including the current transformer ratio (CT) and P/S relay pairs, fault current passing via relays respectively. The PS in this investigation is between [1.5 5]. This assumption is based on the CT ratio and the range of permissible PS values. CTI and a relay's bare minimum working time are both estimated to be 0.2 seconds. TDS is regularly measured between [0.1 1.1]. The BES parameters for this test case are $n_{\text{Pop}} = 50$ and Max_iter $= 1000$. Only TDS is viewed as an optimized variable in this circumstance because PS is fixed. The ideal TDS value, the OF value produced using (9), and the convergence time obtained by utilizing a hybrid LP formulation and BES are listed in Table 2. For the 6-bus test system without violating any constraints, BES provides the best result for the 6-bus system with a value of OF equal to 3.2702 s. IFA converges with a value of 6.4050 s, followed by FA with 7.6866 s. PSO gives a value of 8.1245 s. The hybrid between PSO and DE gives a value of 9.2671 s. The GA-LP algorithm gives 10.7294 s. TLBO yields a suboptimal value of 23.787 s. In contrast, BES achieves convergence within 5.842 seconds and 150 iterations to reach the optimal solution. It should be noted that the computational time for the other compared methods was not specified in the original literature, making a direct comparison of computational speed difficult.

Additionally, the primary and backup operating time are tabulated on Table 3.

4.4 Case 2: IEEE 8-Bus Test Case

In the second case with NLP formulation, the topology, which is an 8-bus system, is different from the previous cases. Both near-end and far-end three-phase fault locations are considered in Figure 4. The system comprises 8 buses, 7 branches, and 14 DOCRs [9]. The parameters of BES selected are $n_{\text{Pop}} = 50$ and Max_iter $= 1000$.

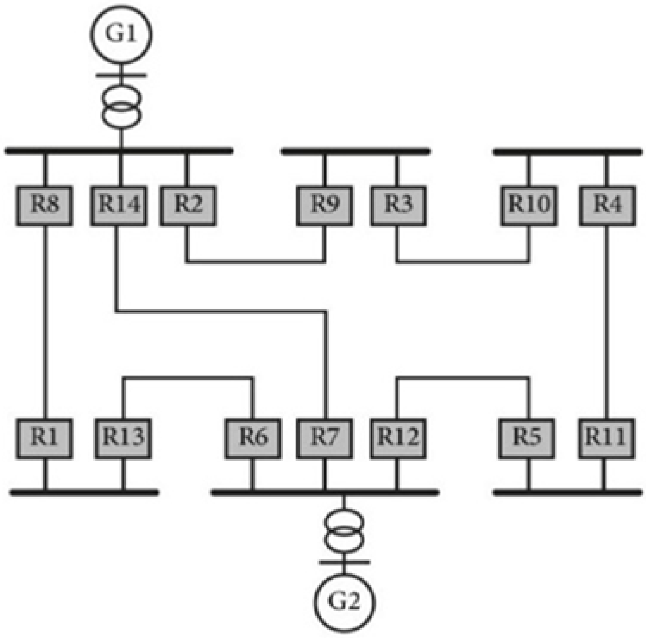

Figure 4. IEEE 8-bus DOCRs coordination problem [9].

The TDS is continuous between $[0.05, 1.1]$, and the PS values are 1.25 and 1.5, respectively. The minimum and maximum operating times are $[0.05, 1]$, respectively.

Table 2. Optimal Setting Result for 6-Bus System by LP Formulation.

Relay	PSO [34]	PSO-DE [10]	TLBO [4]	GA-LP [35]	FA [1]	IFA [1]	BES
TDS_1	0.2602	0.4064	0.3780	0.55647	0.1	0.1002	0.25553
TDS_2	0.4739	0.7506	0.3443	0.5	0.1	0.1002	0.13438
TDS_3	0.2406	0.3872	0.2553	0.5	0.1296	0.1006	0.14087
TDS_4	0.2711	0.4031	0.3346	0.50004	0.1050	0.1102	0.10645
TDS_5	0.1268	0.2005	0.1005	0.50002	0.1007	0.1	0.11600
TDS_6	0.1264	0.2011	0.2376	0.5	0.3880	0.4070	0.17223
TDS_7	0.1265	0.2003	0.3000	0.51584	0.1016	0.1092	0.14104
TDS_8	0.1265	0.2133	0.4720	0.5	0.1	0.1	0.10000
TDS_9	0.1268	0.2006	0.0414	0.50003	0.1128	0.1175	0.13553
TDS_{10}	0.1424	0.2265	0.3323	0.5	0.1001	0.2860	0.10000
TDS_{11}	0.1647	0.2610	0.2518	0.5	0.1143	0.1439	0.13479
TDS_{12}	0.1401	0.2039	0.2704	0.59127	0.2138	0.3404	0.18956
TDS_{13}	0.1265	0.2002	0.1735	0.5	0.1899	0.1063	0.13461
TDS_{14}	0.1779	0.2837	0.2817	0.52268	0.2881	0.4070	0.14735
OF (s)	8.1245	9.2671	23.787	10.7294	7.6866	6.4050	3.2702
Time (s)	NS	NS	NS	NS	NS	NS	5.842

Table 3. Relay Operating Time for 6-Bus System by LP Formulation.

Primary relay	Secondary relay	BES		
		OT_P (s)	OT_S (s)	CTI (s)
1	15	0.37549	0.57550	0.20000
2	17	0.25020	0.45021	0.20001
3	4	0.17808	0.37810	0.20002
4	1	0.17128	0.48620	0.31492
4	6	0.17128	0.41951	0.24823
5	3	0.21951	0.48538	0.26587
5	8	0.21951	0.41951	0.20000
6	23	0.22787	0.49845	0.27058
7	5	0.28620	0.48620	0.20000
7	23	0.28620	0.48620	0.20000
8	10	0.23357	0.48177	0.24820
8	7	0.23357	0.43358	0.20001
9	12	0.20978	0.48205	0.27227
9	9	0.20978	0.43358	0.22380
10	14	0.19163	0.39164	0.20001
11	21	0.16996	0.38707	0.21711
12	11	0.29544	0.49544	0.20000
13	21	0.17917	0.37917	0.20000
14	16	0.28204	0.48205	0.20001
14	19	0.28204	0.48207	0.20002

The CTI is set to be 0.3 s. The data cited in [9] presents the system information for the three faults on each line, including the CT and P/S relay pairs, and the fault current passing via relays, respectively.

The Table 4, displays the results of optimization by BES, ABC-PSO, ABC, and PSO utilizing the objective function of formula (9). In every independent run, BES consistently arrives at a feasible solution without any constraint violations.

In Table 4, BES achieves its optimal value after 20 iterations with an objective function value of 8.1411 s, ABC-PSO, ABC and PSO achieve their optimal values

Table 4. Optimal Setting Result for 8-Bus System by NLP Formulation.

Relay no	PSO [9]		ABC [9]		ABC-PSO [9]		BES	
	TDS	I_p	TDS	I_p	TDS	I_p	TDS	I_p
1	0.351	179.755	0.436	120	0.37	120	0.1	478.64
2	0.465	480	0.424	295.48	0.458	266.4	0.29914	443.48
3	0.746	80	0.496	80	0.398	184.4	0.23429	319.65
4	0.469	120	0.106	353.85	0.263	226.13	0.1551	283.55
5	0.261	120	0.05	335.94	0.206	120	0.10077	201.54
6	0.559	120	0.396	314.9	0.327	380.65	0.32153	123.78
7	0.701	80	0.475	197.38	0.375	228.56	0.27869	281.12
8	0.286	480	0.331	407.62	0.47	120	0.20441	344.21
9	0.05	320	0.221	123.09	0.05	320	0.10005	210.1
10	0.083	480	0.275	245.87	0.157	186.56	0.14453	315.98
11	0.289	120	0.325	325.42	0.165	480	0.20666	474.95
12	0.488	429.206	0.357	480	0.434	120	0.31774	407.97
13	0.338	190.584	0.377	120	0.26	230.95	0.10015	455.72
14	0.419	258.107	0.445	150.2	0.265	319.98	0.28736	289.37
OF (s)	12.8274		11.5723		10.1942		8.1411	
Time (s)	NS		NS		NS		0.623	

NS: Not specified in the literature

with 10.1942 s, 11.5723 s, and 12.8274 s respectively. Table 4 demonstrates the robustness of the BES algorithm compared to other methods. Table 5 shows the operating time and CTI for BES algorithm, we can see that CTI constraints are satisfied in all P/S pairs.

Table 5. Relay Operating Time for the 8-Bus System Using NLP Formulation.

Primary relay	Secondary relay	BES		
		OT_P (s)	OT_S (s)	CTI (s)
1	15	0.40061	0.71116	0.31055
2	17	0.81857	1.34040	0.52183
2	4	0.81857	1.13140	0.31281
3	1	0.68394	1.01850	0.33459
4	6	0.51715	0.83051	0.31336
5	3	0.36618	0.69022	0.32404
6	8	0.58711	1.00870	0.42162
6	23	0.58711	1.18640	0.59933
7	5	0.69912	1.00870	0.30961
7	23	0.69912	1.22390	0.52474
8	10	0.52161	1.13140	0.60978
8	7	0.52161	1.06740	0.54579
9	12	0.35943	0.66288	0.30345
10	9	0.49812	0.89928	0.40116
11	14	0.71260	1.01630	0.30371
12	21	0.84048	1.22390	0.38338
12	11	0.84048	1.18640	0.34597
13	21	0.40727	0.71099	0.30372
14	16	0.72891	1.34040	0.61149
14	19	0.72891	1.06740	0.33849

4.5 Case 3: IEEE 3-Bus Case

In the third topology with MINLP formulation, with three generator, three lines and six overcurrent relays are applied to a 3-node meshed network system, as seen in Figure 5.

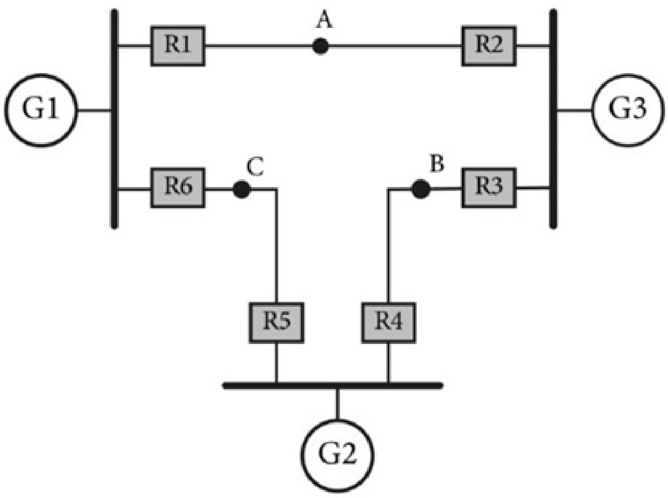

Figure 5. IEEE 3-bus DOCRs coordination problem model [3].

The following criteria are established for BES: $n_{\text{Pop}} = 10$ and Max_iter $= 400$. The parameters to be optimized are TDS and PS since the TDS is continuous from 0.1 to 1.1 and PS is discrete in steps of 0.5 from 1.5 to 5.0. The technical information and P/S relationships for this system are provided in [2]. The data cited

Table 6. Optimal Setting Result for 3-Bus System by MINLP Formulation.

Relay	SBB [2]	Seeker [2]	BBO [6]	BBO-LP [6]	Jaya [3]	HHO [3]	BES
TDS_1	0.1510	0.1070	0.1043	0.1067	0.100	0.100	0.10056
TDS_2	0.1280	0.1080	0.1128	0.1083	0.100	0.100	0.10000
TDS_3	0.1300	0.1000	0.1008	0.1000	0.100	0.100	0.10000
TDS_4	0.1040	0.1000	0.1080	0.1000	0.1119	0.100	0.10725
TDS_5	0.1060	0.1000	0.1008	0.1000	0.100	0.100	0.10000
TDS_6	0.1000	0.1120	0.1030	0.1119	0.100	0.100	0.10000
PS_1	1.5	2.5	3.0	2.5	1.5	1.5	2.0
PS_2	1.5	2.0	2.0	2.0	3.0	3.0	1.5
PS_3	2.0	3.0	3.0	3.0	5.0	3.5	2.0
PS_4	2.5	2.5	3.0	3.0	1.5	2.0	1.5
PS_5	2.5	2.5	2.5	2.5	2.0	2.0	1.5
PS_6	2.0	1.5	2.0	1.5	1.5	1.5	1.5
n_{Pop}	—	50	50	20	20	20	10
Max_iter	—	85	1000	20	50	50	400
OF (s)	1.727	1.599	1.68375	1.59871	1.5477	1.4948	1.3828
Time (s)	NS	10.45	16.23	2.99	0.0286	0.1228	1.207

in [2], present the system information for the three faults on each line, including the CT and P/S relay pairs, fault current passing via relays.

Table 7. Relay Operating Time for the 3-Bus System Using the MINLP Formulation.

Primary relay	Secondary relay	OT_P (s)	OT_S (s)	CTI (s)
1	5	0.24418	0.64696	0.40278
2	4	0.20940	0.40940	0.20000
3	1	0.22282	0.42282	0.20000
4	6	0.24247	0.50885	0.26639
5	3	0.21056	0.43929	0.22873
6	2	0.25337	0.78422	0.53085

Table 6 shows that BES achieves a superior objective function (OF) value of 1.3828 s with $n_{\text{Pop}} = 10$ and Max_iter = 400, while SBB, Seeker, BBO, BBO-LP, JAYA, and HHO achieve their optimal OF values of 1.727 s, 1.599 s, 1.6837 s, 1.5987 s, 1.5477 s, and 1.4948 s, respectively. These results demonstrate the superior efficiency of BES compared with the other approaches. Table 7 further indicates that all constraints of the BES algorithm are satisfied, with no violations observed for any of the relay pairs.

4.6 Case 4: IEEE 3-Bus Test

This case tested a three-bus system taken from [4], which comprises three buses with six overcurrent relays, where a fault analysis is performed at four points (A, B, C, D) in two scenarios. The first scenario, shown in Figure 6, tests the system without distributed generation (DG), while the second scenario, shown in Figure 7, tests the system with the addition of a Synchronous Based Distributed Generator (SBDG) and an Inverter Based Distributed Generator (IBDG). The impact of distributed generation on relay coordination has been studied in [36]. The coordination problem is expressed using MINLP formulations, so the variables to be optimized are TDS and PS, where TDS is continuously between [0.05, 1.2]

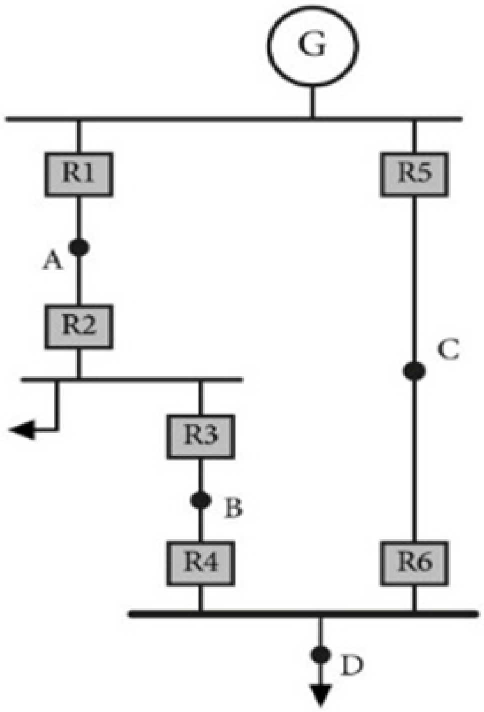

Figure 6. IEEE 3 Bus system model without DG [4].

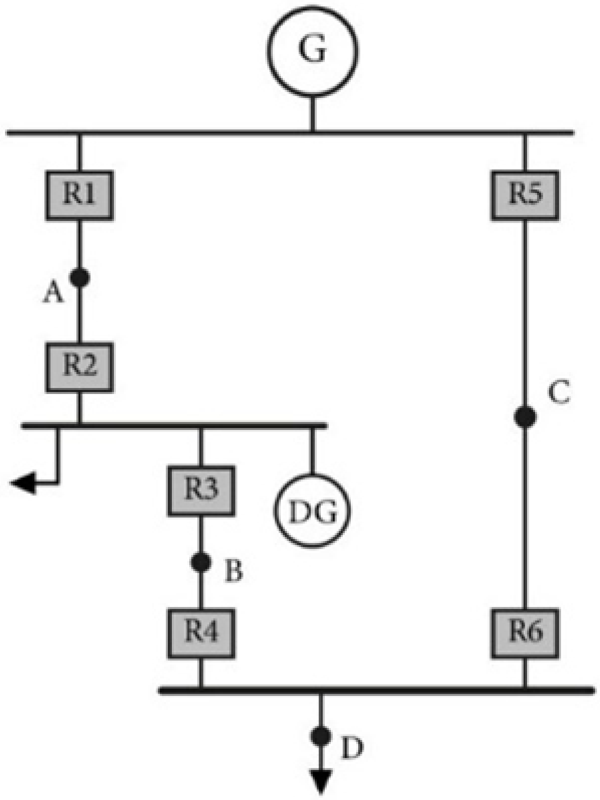

Figure 7. IEEE bus system model with DG [4].

and PS is between 0.5 and 2. The CT of each relay is cited in [4]. BES parameters are configured as follows: $n_{\text{Pop}} = 10$ and Max_iter = 100.

IEEE 3-Bus system without DG

Table 8. Optimal Setting Result for 3-Bus System Without DG by MINLP Formulation.

Relay no	TLBO [4]		BES	
	TDS	PS	TDS	PS
1	0.0706	0.9761	0.050003	0.62106
2	0.0503	0.6001	0.050001	0.50000
3	0.0500	0.6567	0.050000	0.59363
4	0.0500	0.8036	0.050000	0.76543
5	0.0744	0.9947	0.050013	1.16330
6	0.0500	0.6266	0.050000	0.50001
OF (s)	1.7139		1.0471	
Time (s)	NS		0.447	

The IF values are fixed constants that have been predefined in [4], after a fault analysis at the four points (A, B, C, D). The results (optimal settings) obtained are presented in Table 8. It is clear that BES could reach an optimal value of 1.0471 s while respecting the constraints, and a value of 1.7139 s for TLBO, the values of operating time and the coordination time intervals obtained for the 3-bus system without DG are in Table 9, clearly indicate that the CTI constraint is satisfied in each P/S pair by BES without violation.

Table 9. Relay Operating Time for the 3-Bus System Without DG.

Fault point	Primary Relay		Secondary Relay		CTI (s)
	Relay no	OT_P (s)	Relay no	OT_S (s)	
A	2	0.18734	4	0.48735	0.30000
B	3	0.26435	1	0.61176	0.34741
B	4	0.32898	5	1.17690	0.84787
C	6	0.26646	3	0.56647	0.30000
D	3	0.26435	1	0.61176	0.34741

IEEE 3-Bus system with DG

For this case a fault analysis at the four points (A, B, C, D) was performed by adding a Synchronous Based Distributed Generator (SBDG) and an Inverter Based Distributed Generator (IBDG) separately. The IF obtained is cited in [4]. The TDS and PS are the variables to be optimized; the optimal settings obtained by BES and the corresponding OF values are presented in Table 10, the operating time and the coordination time interval values obtained for the three-bus system with DG are in Table 11, clearly indicate that the CTI constraint is satisfied in every P/S pair by BES. The sum of operating time of primary relays obtained for this case has been compared to the other optimization algorithm TLBO used in [4] as illustrated in Table 12, and indicates that BES achieves a more optimal objective function value than the competing technique.

Table 10. Optimal Setting Result for 3-Bus System With DG by MINLP Formulation.

Relay no	With SBDG BES		With IBDG BES	
	TDS	PS	TDS	PS
1	0.13888	0.50743	0.09384	0.50000
2	0.050002	0.50001	0.050003	0.50000
3	0.050021	0.73337	0.050000	0.58866
4	0.051476	0.70925	0.050020	0.72769
5	0.121290	1.04510	0.180040	0.50007
6	0.050004	0.50048	0.197620	0.50000
OF (s)	0.87866		0.95871	
Time (s)	0.483		0.484	

The OF value obtained by BES with SBDG is 0.87866 s, compared to 0.9336 s for TLBO. For the case with IBDG, the OF value obtained by BES is 0.95871 s, compared to 1.0800 s for TLBO. These results clearly demonstrate that BES outperforms TLBO in both scenarios.

Table 11. Relay Operating Time for the 3-Bus System With DG by MINLP Formulation.

Fault point	Primary relay	Secondary relay	With SBDG BES			With IBDG BES		
			OT_P (s)	OT_S (s)	CTI (s)	OT_P (s)	OT_S (s)	CTI (s)
A	2	4	0.17039	0.47048	0.30009	0.17838	0.47849	0.30011
B	3	1	0.23925	0.54574	0.30649	0.26020	0.61478	0.35457
B	4	5	0.24822	0.80532	0.55710	0.28242	0.86325	0.58083
C	6	3	0.22079	0.52085	0.30005	0.23771	0.53777	0.30006
D	3	1	0.25420	0.86496	0.61076	0.26020	0.61478	0.35457

Table 12. Optimal Setting of 3-Bus System Compared to TLBO Method.

		TLBO [4]	BES
OF (s)	With SBDG	0.9336	0.87866
	With IBDG	1.0800	0.95871

5 Conclusion

This research examines the efficacy of the novel Bald Eagle Search (BES) optimization approach, applied for the first time to tackle the directional overcurrent relay (DOCR) coordination problem. The study investigates five systems featuring DOCR, including cases with 6 buses, 8 buses, and 3 buses, both with and without distributed generation (DG), using various LP, NLP, and MINLP formulations. The results indicate that the BES optimizer demonstrates remarkable efficiency and consistency, as evidenced by the objective function values obtained across all cases. Comparing the objective function with other optimization techniques, BES consistently yields the minimum objective value, demonstrating its superior ability to optimize with rapid convergence.

Regarding computational times, the proposed approach is primarily envisaged for offline protection planning and periodic relay setting revisions. However, the rapid convergence speed demonstrated by BES across varying network scales suggests high scalability, indicating potential future adaptability for near-real-time adaptive protection schemes in smart grids. Remarkably, the proposed method adheres to all constraints, ensuring proper coordination.

Looking ahead, the BES could be further enhanced to address the challenges posed by directional overcurrent relays in more intricate energy networks, including the integration of renewables, distributed generation (DG), and flexible alternating current transmission systems (FACTS).

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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