Optimal coordination of directional over current relays for distribution systems using hybrid GWO-CSA

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Article Info

Article history:

Received Aug 5, 2023
Revised Nov 21, 2023
Accepted Dec 7, 2023

Keywords:

Coordination
Cuckoo search algorithm
Distributed generation systems
Grey wolf optimization
Optimal relay setting
Over current relays

ABSTRACT

Coordination of protective relays is a critical aspect of electrical distribution systems, ensuring effective and reliable protection against faults. In modern power systems, the integration of distributed generation (DG) sources adds complexity to the coordination task. The dynamic nature of DG systems requires adaptive relay settings that can swiftly detect and isolate faults while minimizing potential damage and downtime. The purpose of this research is to improve the coordination of directional over current relays in electrical distribution systems, particularly in DG systems. An optimization technique combining the grey wolf optimization (GWO) and cuckoo search algorithm (CSA) is developed to identify the best relay settings that reduce overall operation time while ensuring excellent fault identification and isolation. To address relay faults caused by DG integration, a suitable primary and backup relay design is chosen, and the influence of time multiplier settings (TMS) on system performance and reliability is investigated. The proposed GWO-CSA technique is evaluated and implemented on IEEE 3, 8 and 15-bus systems using MATLAB. Simulation results show that the GWO-CSA strategy outperforms well compared to previous algorithms, enabling optimal coordination and increased protection in DG systems while drastically lowering relay operating time.

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1. INTRODUCTION

The current paradigm of electrical power distribution network (EPDN) planning, management, and control is based on the premise of unidirectional power flows transported from higher voltage levels to consumption levels. EPDNs are typically designed in a radial configuration, facilitating the implementation of straightforward and cost-effective protection methods that ensure selective operation of the protection system [1]. Over-current relays (OCRs) play a crucial role in EPDNs, serving as both primary and secondary protection mechanisms. If the primary relay fails to operate within the specified time period, the backup protective relay is activated. When a fault occurs within the backup relay's protection zone, it must conform to the coordination time interval (CTI) [2]. It is essential for OCRs to operate swiftly and be capable of coordination with other relays to enhance system dependability, thereby improving the speed and reliability of the overall protection strategy. A variety of methods for OCR coordination have been suggested. Three categories can be made out of these techniques: optimization, topological analysis, and trial-and-error [3]. However, in the first two classes' solutions, the plug multiplier setting (PMS) or pickup setting (PS) and time multiplier setting (TMS) were manually determined using expert knowledge or analytical computation to ensure the optimal relay coordination.

Today, the EPDN is so complicated that using the traditional relay coordination mechanism is not advised. As a result, effective relay coordination is crucial for adaptation [4]. The practical advantage of Meta heuristic methods resides in their efficacy and broad applicability. Meta heuristic approaches are designed to address difficult optimization problems by providing near-optimal solutions in reasonable computation times. The seeker algorithm, differential evolution, genetic algorithm, and particle swarm optimization have all been used to solve the DOCR coordination problem in more recent work. Analytical optimization approaches such as linear (LP) and non-linear programming (NLP), in contrast to meta heuristics, ensure convergence to a local or global optimum depending on the problem model and the supplied initial point. In the linear programming approach, only TMS is employed as a continuous variable, whilst PS is kept constant based on prior knowledge [5]. Using the linear programming methodology, the Big-M [6], [7], dual simplex [8], [9], modified jaya algorithm [10], and other optimization techniques have been used to discover the optimal TMS values. In the non-linear programming approach, TMS and PS both serve as decision variables.

Researchers used the following techniques to find the best relay settings, which include both TMS and PS, by taking into account the non-linear programming methodology. In this field, genetic approach (GA) quickly rose to prominence in the early 1990s. The continuous genetic approach (CGA), an improvement to this approach, has been developed in [9]. As the chromosome doesn't have to be decoded, CGA produces findings faster than binary GA. Alkaran *et al*. [10] developed the fuzzy-based Genetic Algorithm technique as a remedy to the miscoordination problem, which caused the weighting parameters to shift throughout simulation. Moravej *et al*. [11] introduces particle swarm optimization (PSO), the following phase in the bio-nature inspired technique. A modified differential evolution algorithm with an information exchange strategy was proposed. Instead of using a single population, several sub populations which enhance the explorative power of the algorithm were used [12]. The invasive weed optimization (IWO) algorithm has been adapted for the high dimension coordination problem [13]. It has been demonstrated that the PSO produces better results than both traditional and contemporary GA. Differential evolution (DE), modified differential evolution (MDE), and invasive weed optimization (IWO) continue the algorithm's revolution. Hybrid methods have been developed in [14], [15] to improve MDE performance. Ahmarinejad *et al*. [16], the cuckoo search algorithm (CSA) is devised. Improved GSO and the electromagnetic field optimization (EFO) approach have also been introduced in recent years [17], [18]. All of these algorithms were developed in an effort to identify the best over current relay setting. The grey wolf optimization (GWO) technique, a new reliable and trustworthy algorithm, was recently introduced. This GWO approach has been applied to issues in optimal reactive power dispatch [19], integrated economic emission dispatch [20], and biomedical engineering [21]. Mirjalili *et al*. [22] presented GWO, which was motivated by a pack of wolves' hunting techniques. To increase the rate at which the searching agents explore, some modifications to the traditional GWO have been made. Conventional GWO has been found to have slow convergence and frequently become stuck in local optimal. Instead of acting as the top three agents' followers, the suggested enhancement expanded the number of searching agents.

This study seeks to find the best TMS and PS value in order to reduce the objective function. This study investigates the system's performance and dependability in connection to the time multiplier settings (TMS) of directional over current relays. To overcome relay difficulties caused by DG penetration, an appropriate primary along with backup relay configuration is chosen. The proposed GWO-CSA technique is tested on IEEE 3,8 and 15 bus systems using MATLAB. The simulation results indicate that using the GWO-CSA hybrid technique significantly reduces relay operation time and performs using the GWO and CSA methods individually. This result demonstrates how well the suggested technique works to achieve the best coordination and enhanced security in DG systems.

2. PROBLEM FORMULATION

The primary goal of DOCR issue formulation is to determine the best peak-up current setting and time-dial setting for primary relays, that are often positioned closest to the fault's site. If the primary relay coordination fails, one or more of the other relays can serve as a backup, keeping the fault current from spreading to the rest of the network. Primary relay close-in and far bus fault coordination is frequently sub classified. This is widely used in literature to describe an acceptable relay coordination objective function, as will be demonstrated later in this work. This imposes a limitation on relay behaviour, ensuring that a primary relay always take precedence over its corresponding back-up equivalent. Because the DOCR problem is non-convex, a hybrid GWO-CSA approach is created in MATLAB and tested on IEEE 3, 8, and 15-bus systems.

2.1. Objective function

Overall, the coordination of directional over-current relay in power systems has been stated as an optimization problem, with the goal of minimizing the sum of the working times of the system's relays during a malfunction, denoted by the symbol 'tz'. Near end faults are typically taken into account. It can be expressed mathematically as given in (1).

$$\text{Minimize } t_z = \sum_{m=1}^{n} W_m\, t_{m,l} \tag{1}$$

In this context, n represents the total number of relays in the distribution system. The goal is to minimize the target function t_z. For this purpose, the operating time of the primary relay for faults in zone l and near end faults is denoted as $t_{m,l}$, where m corresponds to a specific relay and l represents a particular zone. Each relay Rm is assigned a weight W_m to quantify its importance in the overall scheme. Considering that distribution system lines are short and have nearly equal lengths, the probability of a fault occurring on any line is assumed to be the same. Based on this assumption, equal weights are assigned to all relays, denoted by W = 1 for each relay [23], [24]. This approach is a typical strategy used in such scenarios.

2.2. Constraints

2.2.1. Coordination constraints

The system's relays must be coordinated according to the requirement as given in (2). Where $t_{m,l}$ represents the operating time of the primary relay at zone l for a near-end fault, while $t_{p,l}$ represents the operating time of the backup relay in the same zone for the same fault. The selective time interval (STI) is a time range that lies between 0.1 and 0.5. The value of STI is determined by how quickly the circuit breakers operate in the system. This interval is crucial to ensure proper selectivity in relay coordination, where the primary relay should operate faster than the backup relay within the STI to isolate the fault without any interference from the backup relay.

$$t_{p,l-t_{m,l}} \geq STI \tag{2}$$

Relays require a specific amount of time to operate. However, the time it takes for them to operate should not be excessive. This places a constraint on the operating time as shown in (3).

$$tm, n_{m,l,max_{m,l,min}} \tag{3}$$

Where $t_{m,l,max}$ is the maximum working period of the relay at bus P for a local fault and $t_{m,l,min}$ is the lowest operating time. This additionally pertains to other relays.

2.2.2. Relay characteristics

The relays are taken to be identical and to possess typical inverse definite minimum time (IDMT) properties, which are expressed by (4).

$$t_{opt} = \frac{0.14*(TMS)}{PSM^{(0.02)}-1} \tag{4}$$

Where t_{opt} is the duration of the relay. Standard IDMT relay characteristics use the constants 0.14 and 0.02. PSM stands for the plug setting multiplier which is calculated using (5), and TMS is for the time multiplier setting.

$$PSM = \frac{I_{relay}}{PS} \tag{5}$$

In the form of the previously indicated (4), the issue is non-linear. The relay coordination problem can be expressed as a linear programming problem if the plug setting (PS) of the relays is fixed as well as the working time of the relays is regarded to be a linear function of the duration multiplier setting [25], Because PSM is fixed in the linear problem, the operating time is calculated using (6), where α_m is shown in (7).

$$t_{opt} = \alpha_m(TMS) \tag{6}$$

Where,

$$\alpha m = \frac{0.14}{PSM^{(0.02)}-1} \tag{7}$$

As a result, the objective function may be expressed as shown in (8).

$$t_z = \sum_{m=1}^{n} \alpha m(tms)_m \tag{8}$$

Subject to the limitations specified in (2) and (3).

3. HYBRID GREY WOLF OPTIMIZATION ALGORITHM AND CUCKOO SEARCH ALGORITHM (GWO-CSA)

It has become more and more common to combine two or more algorithms to find the best answers to optimization issues. Numerous well-known optimization techniques have been included into hybrid optimized algorithms, making them more effective in addressing the problems. The GWO algorithm simulates the leadership structure and hunting behavior of grey wolves. In the wild, grey wolves coexist in packs comprising four different species. The dominant wolf, known as the alpha (α), holds the highest position in the pack's hierarchy. The alpha is responsible for critical social decisions, such as food distribution and dealing with potential threats. Next in the hierarchy is the beta, who serves as the alpha's aide and assists in maintaining control over the group. The beta commands the other wolves but must always respect and follow the alpha's leadership. The third level wolf is the delta (δ), who must comply with the requests of both the alpha and the beta. After their useful lifetimes are over, the alpha and beta are degraded to delta status. At the base of the pyramid is the omega (ω), and the rest of the group must accept omega's submission.

The GWO algorithm is inspired by this grey wolf pack's hunting behavior and utilizes three types of wolves for searching the solution space: the alpha wolf, the beta wolf, and the delta wolf. On the other hand, the cuckoo search or CS algorithm is a different meta heuristic approach. It is inspired by the behavior of cuckoos, specifically their compulsory brood parasitism behavior. CS employs Lévy flying to generate new ideas and explore the solution space. Both GWO and CS are popular meta heuristic algorithms with distinct search strategies, making them effective in different optimization scenarios [26], [27].

Numerous studies have highlighted the strengths of the cuckoo search (CS) algorithm in global exploration and the grey wolf optimization (GWO) algorithm in exploitation [28]–[31]. In this study, the GWO approach was employed to optimize the size of system components while minimizing costs and meeting load demands. However, GWO's tendency to fall into local optima when inspecting individuals with high fitness values can limit its global search ability. To overcome this limitation and enhance the GWO algorithm, a hybrid approach called grey wolf optimization with cuckoo search optimization (GWCSO) was proposed. In GWCSO, the cuckoo search algorithm (CSA) is used to modify the location of nests, allowing for more efficient jumping between different search areas. By integrating CSA, GWCSO achieves robustness and fast optimization for sizing units of solar PV, wind turbines, storage batteries, and biomass gasifiers in a grid-connected micro grid (MG). The collaboration between GWO and CSA is depicted in Figure 1, where the positions, speeds, and convergence accuracy of grey wolf agents are adjusted using CSA's position update equation. This hybrid approach ensures an effective and swift solution to optimization problems, making it well-suited for the application at hand. The GWO algorithm's fitness function determines the "degree of grey" to identify the best solutions represented by alpha, beta, and delta wolves. These wolves form the key-group, while the remaining members are represented by the omega wolf. Mathematical models inspired by grey wolf social hierarchy and hunting behavior are used to design and optimize the GWO algorithm. Encircling behavior during hunting is expressed using specific in (9) and (10).

$$E = |D.Yp(t) - Y(t)| \tag{9}$$

$$Y(t+1) = |Yp(t) - B.E| \tag{10}$$

In both of these equations, Y represents the location of a single wolf, and t + 1 represents the future iteration. The prey's location is represented by Yp, while the coefficient vectors are represented by B and E. The (11) and (12) model the calculation process.

$$B = 2b.r1 - b \tag{11}$$

$$D = 2.r2 \tag{12}$$

During the iterative procedure of the GWO algorithm, random integers r1 and r2, ranging between 0 and 1, are used. If vector b is assigned a value between 2 and 0, the iterative process results in a linear decrease in the number of iterations.

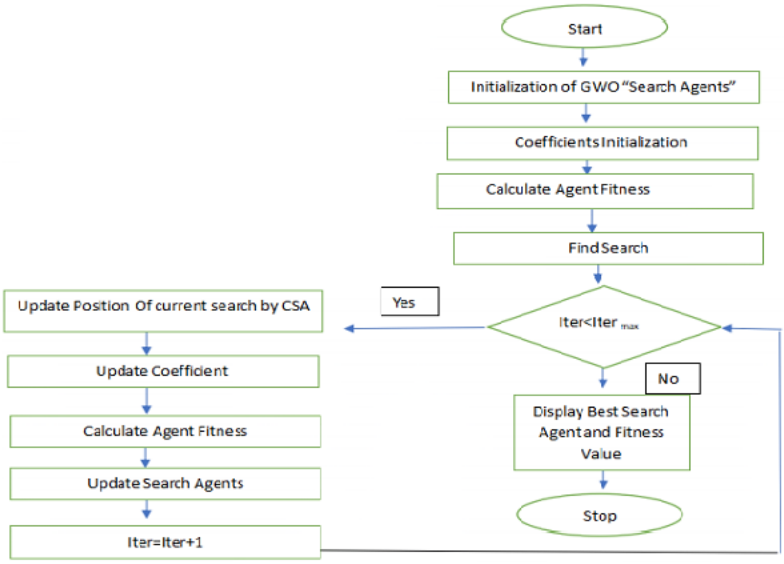

Figure 1. Flow chart of hybrid grey wolf optimization algorithm and cuckoo search algorithm

When the wolf pack discovers prey, the alpha, beta, and delta wolves take the lead in encircling it. They possess knowledge of the prey's location. These best three solutions are combined to form a key group, which is then employed to update the position of each wolf within the group. The following (13)-(16) are used to update the position of the wolves:

$$Y(t+1) = (Y1 + Y2 + Y3)/3 \quad (13)$$

$$Y1 = |Ya - B1 - Ea| \quad (14)$$

$$Y2 = |Yb - B2. Eb| \quad (15)$$

$$Y3 = |Ys - B3. Es| \quad (16)$$

Where Ya, Yb, and Ys represent the top three results from the iterative process thus far, which comprise the key group. The mathematical (17)-(19) that follow describe additional parameters.

$$Ea = |D1. Ya - Y| \quad (17)$$

$$Eb = |D2. Yb - Y| \quad (18)$$

$$Es = |D3. Ys - Y| \quad (19)$$

The movements of grey wolves when they approach their prey with respect to the maximum number of iterations (Max) can be represented by (20).

$$B = 2 - 2\left(\frac{t}{Max}\right) \quad (20)$$

The (13) depicts how the GWO algorithm adjusts the positions of the key group individuals with high fitness values. However, it may lack effective global search capabilities and might get trapped in local optima, especially when dealing with large datasets. On the other hand, the CS approach uses random walks and Levy flights to move nests, with the search path length being arbitrary and having nearly equal probabilities of being longer or shorter than previous paths. This randomness makes the movement from one location to another more straightforward. Initially, cuckoo birds select their nests at random and only lay one egg at a time. Second, only the best nests will endure for upcoming generations. Thirdly, both the quantity of bird nests and the likelihood that the eggs will be found are fixed. When a foreign egg is discovered, the host bird abandons the nest and builds another. The following equations are used to update the nests throughout iteration while adhering to these three requirements:

The CS process evolves a population of N individuals from a starting point (k = 0) to an overall number of iterations (gen) known as Ek(Y k 1, Yk2,...., Y kN). Each individual Yki (i [1,..., N]) has the dimensions (Yki,1, Yki,2,...., Yki,n), where (Yki,1, Yki,2,...., Yki,n) is a decision variable in the optimization problem to be solved. Each individual, Yki (candidate solution), is assessed using an objective function, f(Y ki), the output of which represents Y ki's fitness value. The use of Levy flights to generate new candidate solutions is one of the most advanced components of cuckoo search. By shifting the current Yk i, a new candidate solution, Yki (i[1,...., N]), is generated. A symmetric Levy distribution produces qi, a random step, to produce ci. To produce qi, Mantegna's algorithm is employed which is by (21).

$$qi = \frac{v}{|w|^{1/b}} \tag{21}$$

Where w is an n-dimensional vector having 3/2 dimension and v is an n-dimensional vector with v1, v2 dimensions. The normal distributions shown in (22) and (23) are used to determine each element of w and v.

$$v{\sim}N(0,\delta_v^2), w{\sim}N((0,\delta_w^2) \tag{22}$$

$$\delta v = \frac{\Gamma(1+b).\sin\left(\pi.\frac{b}{2}\right)}{\Gamma\left(\frac{(1+b)}{2}\right).b.2^{(b-1)/2}}, \delta w = 1 \tag{23}$$

Where Γ (.) represents the gamma distribution. After determining si, the necessary adjustment to position Di is determined as in (24):

$$D_i=0.01s_i+(Y_i^k-Y^{best}) \tag{24}$$

Where Ybest denotes the best solution identified thus far in regard to fitness value, whereas the product is composed of entry-wise multiplications. Finally, as shown in (25) is used to identify the new candidate solution, Yk+1i.

$$Y_i^{k+1}=Y_i^k+D_i \tag{25}$$

The CS algorithm's step changes, characterized by short-distance detection and infrequent long-distance walking, allow for efficient exploration of the solution space. As the algorithm progresses, the step length increases significantly with time, leading to rapid and extensive exploration of potential solutions. This adaptive behavior enables CS to quickly cover a large search space and find promising regions with potential optimal solutions. By balancing short-distance local exploration and occasional long-distance global exploration, the CS algorithm can effectively and rapidly locate solutions to optimization problems. The hybrid of GWO-CSA algorithm is developed and pseudo code is as given in the following:

Initialize GWO and CSA parameters (population size, and iterations)
Initialize the positions of grey wolves (GWO population)
Initialize the positions of cuckoos (CSA population)
Evaluate fitness of each GWO wolf and CSA cuckoo
While stopping criteria are not met:
Sort GWO and CSA populations by fitness
Perform GWO operations:
For each grey wolf:
Update wolf's position using GWO equations
Boundary checking and fitness evaluation
Perform CSA operations:
For each cuckoo:
Explore a new solution using Levy flight or other CSA methods
Boundary checking and fitness evaluation
Select top solutions from both populations based on fitness
Combine selected solutions to form a merged population
Apply GWO and CSA operations to the merged population:
For each solution:
With a probability P_gwo, perform GWO operation (e.g., search for prey)
With a probability P_csa, perform CSA operation (e.g., lay an egg)

Evaluate fitness of solutions in the merged population
Select the top solutions from the merged population
End while
Return the best solution found

The pseudo code of the GWO-CSA hybrid algorithm is developed for the total operating time minimization and results are analyzed. The following section details the results and discussion obtained from the optimization solution.

4. RESULTS AND DISCUSSION

Relay coordination for 3 bus, 8 bus and 15 bus system is developed using the GWO-CS algorithm. Minimization of total operating time using the TMS as the independent variable for the optimization problem using GWO-CSA algorithm is developed and the results are tabulated to compare with the previous implementation. MATLAB based implementation is carried out to obtain the optimized TMS values for the minimized total operating time objective function given in (8) considering the inequality constraints as given in (2) and (3). The 3 bus system has 6 relays, 8 bus system has 14 relays and 15 bus system has 42 relays. Three cases are considered for the implementation of relay coordination of 3 bus system, 3 bus (Case 1: Without DG, Case 2: With synchronous based distributed generation (SBDG), and Case 3: With inverter based distributed generation (IBDG); 15 bus (Case 1: With DG); and 8 bus (Case 1: Without DG).

Figure 2 depicts the IEEE 3 bus test feeder with three buses, generators, three lines, and six relays. Shunt faults occurring on the power supply are immediately detected by both the primary and backup relays. The primary relay responds faster due to its shorter operating time compared to the backup relay. The system uses this protection scheme to ensure rapid fault detection and isolation, maintaining the stability of the distribution system. The faults points for the 3-bus system are denoted as A, B, C and D, while relays are denoted as R1, R2, R3, R4, R5, and R6 in Figure 2.

Figure 3 [32] illustrates the single line diagram of the 8-bus distribution system, which serves as second test system. The current transformer ratio of the 8-bus system is as given in the Table 1 [32]. The 8-bus system with 14 relays denoted as R1, R2 …R14 with two generators are as given in Figure 3. Within this system, there are two primary generation sources accompanied by two transformers, seven lines, and a total of 14 relays for protection and control. Specifically, the current transformer ratios, representing the minimum and maximum values of TMS, have been precisely set at 0.1 and 1.2, respectively. The efficiency and stability of the system depend on proper coordination based on fault current levels. The fault current of both the primary and the backup relay of the 8-bus system is as given in Table 2. The examination of a much more complex system to show the flexibility and efficacy of the suggested technique using 15 buses is discussed. This 15-bus system is protected by a network of 42 relays and connected by 21 distribution lines which is shown graphically in Figure 4 [33]. This system serves as a model for DG integrated distribution network. The fault currents for primary relay and secondary relays are shown in Table 3.

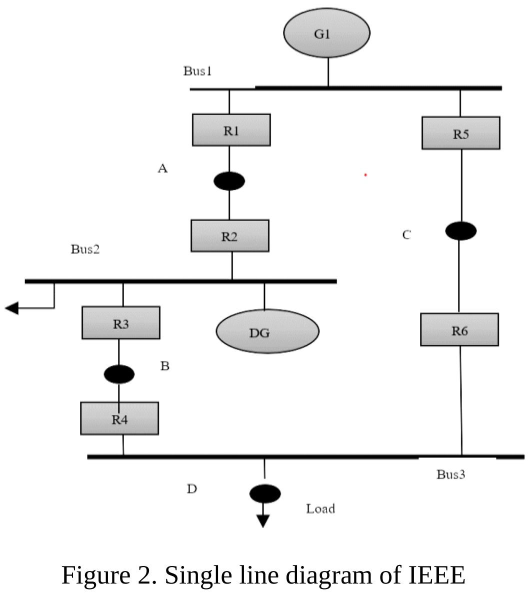

Figure 2. Single line diagram of IEEE 3 bus system

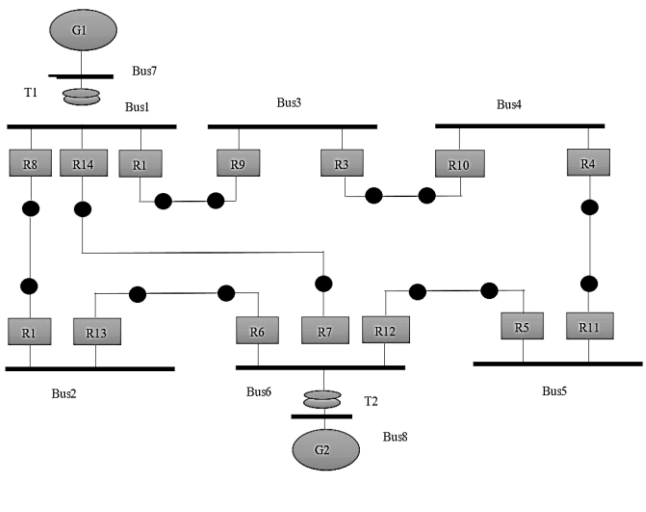

Figure 3. Relay coordination diagram for 8 bus system [32]

Table 1. Relay and its current transformer ratio (CTR) for 8 bus system [32]

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

Table 2. Relay and its fault current for 8 bus system

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

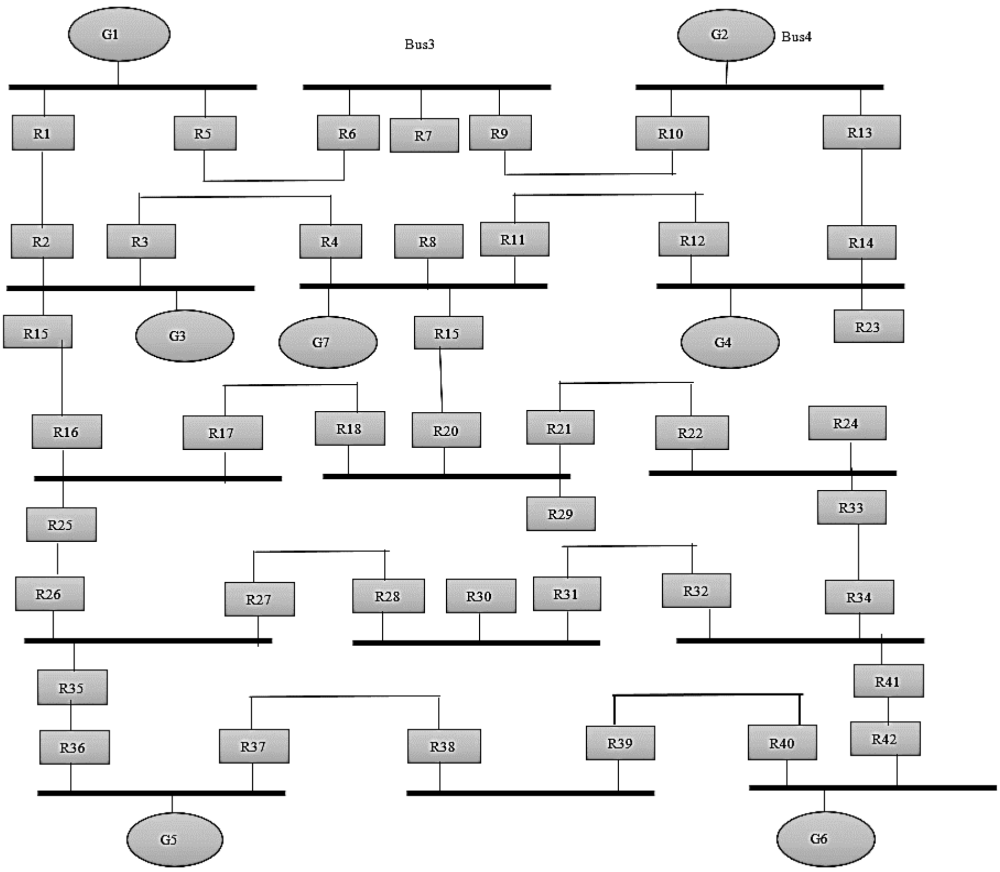

Figure 4. Relay coordination diagram for 15 bus system [33]

Table 3. Relay and its fault current for 15 bus system [33]

Primary relay	Fault current (A)	Backup relay	Fault current (A)	Primary relay	Fault current (A)	Backup relay	Fault current (A)
1	3621	6	1233	20	7662	30	681
2	4597	4	1477	21	8384	17	599
2	4597	16	743	21	8384	19	1372
3	3984	1	853	21	8384	30	681
3	3984	16	743	22	1950	23	979
4	4382	7	1111	22	1950	34	970
4	4382	12	1463	23	4910	11	1475
4	4382	20	1808	23	4910	13	1053
5	3319	2	922	24	2296	21	175
6	2647	8	1548	24	2296	34	970
6	2647	10	1100	25	2289	15	969
7	2497	5	1397	25	2289	18	1320
7	2497	10	1100	26	2300	28	1192
8	4695	3	1424	26	2300	36	1109
8	4695	12	1463	27	2011	25	903
8	4695	20	1808	27	2011	36	1109
9	2943	5	1397	28	2525	29	1828
9	2943	8	1548	28	2525	32	697
10	3568	14	1175	29	8346	17	599
11	4342	3	1424	29	8346	19	1372
11	4342	7	1111	29	8346	22	642
11	4342	20	1808	30	1736	27	1039
12	4195	13	1503	30	1736	32	797
12	4195	24	753	31	2867	27	1039
13	3402	9	1009	31	2867	29	1828
14	4606	11	1475	32	2069	33	1162
14	4606	24	753	32	2069	42	907
15	4712	1	853	33	2305	21	1326
15	4712	4	1477	33	2305	23	979
16	2225	18	1320	34	1715	31	809
16	2225	26	905	34	1715	42	907
17	1875	15	969	35	2095	25	903
17	1875	26	905	35	2095	28	1192
18	8426	19	1372	36	3283	38	882
18	8426	22	642	37	3301	35	910
18	8426	30	681	38	1403	40	1403
19	3998	3	1424	39	1434	37	1434
19	3998	7	1111	40	3140	41	745
19	3998	12	1463	41	1971	31	809
20	7662	17	599	41	1971	33	1162
20	7662	22	642	42	3295	39	896

4.1. Result analysis of 3- bus system

The relay coordination problem was solved using GWO-CSA. In each case the number of search agents were taken as 50 and the number iterations were taken to be 100. From Tables 4 and 5 it can be inferred that the operating time of each relay is reduced when DG is connected to the system since the fault current increases. The total operating time with SBDG reduces by 44.36% when DG is not connected and 5.53% with IBDG.

Table 4. Operating time (OT), time multiplier setting (TMS) of relays for 3 bus system

OT in Sec Case 1	OT in Sec Case 2	OT in Sec Case 3	TMS Case 1	TMS Case 2	TMS Case 3
1.1457	1.1211	1.9226	0.0502	0.0497	0.0502
0.3100	0.2517	0.2842	0.0512	0.0481	0.0506
4.9533	1.5935	3.8774	0.0502	0.0495	0.0502
1.2220	1.1204	1.2370	0.0501	0.0485	0.0501
0.4426	0.3373	0.3927	0.0501	0.0530	0.0501
0.5795	0.3903	0.4602	0.0503	0.0488	0.0502

Table 5. Total operating time (TOT) for all cases 3 bus system

Case	TOT in Seconds
1	8.6531
2	4.8143
3	8.1741

These tables offer valuable insights into how the introduction of a SBDG influences the currents and associated constants during fault conditions at different locations within the power system. The comparative data aids in assessing the impact and benefits of SBDG integration on system performance and fault management. The operating time of all the relays for all the faults are optimized and are compared for all the three cases like without DG, with SBDG and IBDG. The results shows that operating time is reduced since the TMS is optimized.

From the convergence graphs shown in Figures 5-7, it is clear that the proposed GWO-CSA technique Convergence fast for the better TMS with minimized total operating time. The total operating time for all the above said 3 cases were compared. Results show that the operating time with SBDG is reduced by 3.71 seconds when compared with the system when DG not connected and with IBDG its reduced by 0.47seconds.

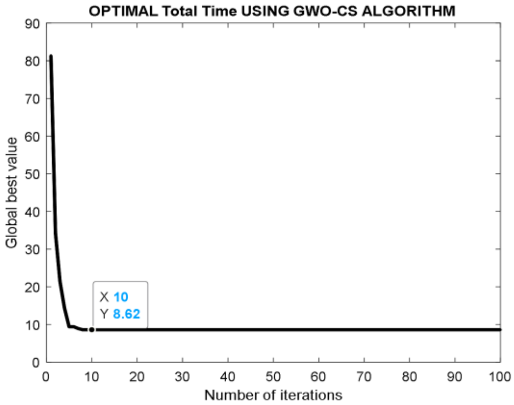

Figure 5. Convergence graph for case 1

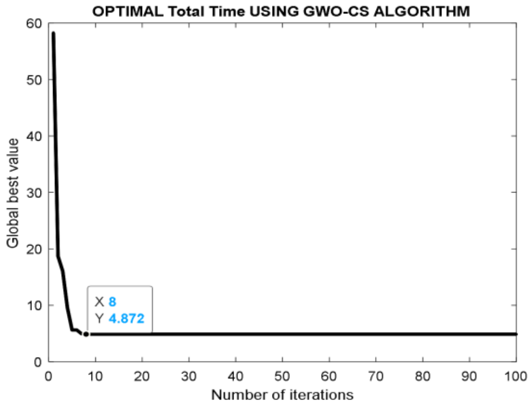

Figure 6. Convergence graph for case 2

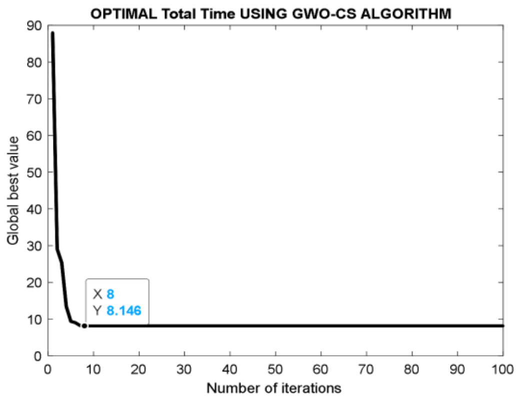

Figure 7. Convergence graph for case 3

4.2. Result analysis of 15- bus system

Table 6 summarizes the results achieved for the total operating time minimization problem for 15 bus system. The optimized TMS values are both tabulated. Each relay's operating time during the fault situation is recorded TMS is the independent variable, and operating time is calculated from TMS values. The convergence graph of the total operating time minimization is shown in Figure 8. The objective function converges at 160 th iteration and out performs better by reducing the operating time which is shown in Figure 8.

4.3. Result analysis of 8 bus system

Table 7 gives the optimized operating time and TMS for the 8 bus system for different faults. Figure 9 shows the convergence graph for the 8 bus system. An optimized TMS can be able to obtain using GWO-CSA when compared with WOA and HWOA techniques, this comparison can be seen Table 8. GWO-CSA gives better optimized operating time by optimizing TMS when compared to other well-known techniques which can be observed in the Table 9. A reduction of 45% in the operating time can be observed compared to WOA and HWOA techniques.

In essence, GWO-CSA employs advanced optimization techniques to fine-tune TMS values for relays, ultimately leading to minimized operating times and improved system performance. The tables serve as valuable references for analyzing the impact of these optimizations and comparing results across various scenarios. These outcomes are presented across distinct scenarios, shedding light on the effectiveness of the optimization techniques employed in each case.

Table 6. Operating time and TMS

Relay number	Operating time in seconds	TMS
1	0.3191	0.0508
2	0.4074	0.0548
3	0.3134	0.0599
4	0.1832	0.0783
5	0.3461	0.0642
6	0.3881	0.0758
7	0.8978	0.0785
8	0.4826	0.0810
9	0.2879	0.0729
10	0.5251	0.0565
11	0.1559	0.0666
12	0.2373	0.1001
13	0.4219	0.0720
14	0.3615	0.0546
15	0.4811	0.0666
16	0.5631	0.0572
17	0.7916	0.0885
18	0.2523	0.0609
19	0.2461	0.1172
20	0.1204	0.0565
21	0.3072	0.0502
22	0.4755	0.0723
23	0.8181	0.0679
24	0.7226	0.0502
25	0.5237	0.0577
26	0.4648	0.0512
27	0.386	0.0692
28	0.4053	0.1826
29	0.135	0.0652
30	0.3206	0.1457
31	0.5253	0.0564
32	0.4979	0.0503
33	0.2075	0.0906
34	0.2594	0.1174
35	0.4792	0.0833
36	0.3162	0.0547
37	0.4453	0.0831
38	0.3293	0.0632
39	0.4646	0.0615
40	0.1368	0.06
41	0.2932	0.0567
42	0.1278	0.0571
Total operating time in seconds	16.8	

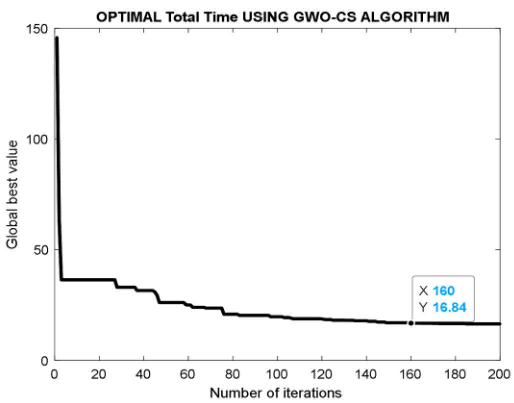

Figure 8. Convergence graph for 15 bus system

Table 7. Comparison of operating time

Relay number	Operating time in seconds	TMS
1	0.1377	0.0526
2	0.2498	0.0539
3	0.2558	0.0537
4	0.2775	0.0511
5	0.1537	0.0517
6	0.2086	0.0998
7	0.3549	0.0476
8	0.1951	0.0407
9	0.3347	0.0564
10	0.2557	0.0477
11	0.2959	0.0540
12	0.2492	0.0543
13	0.1348	0.0499
14	0.1187	0.0612
Total operating time in seconds	3.22	

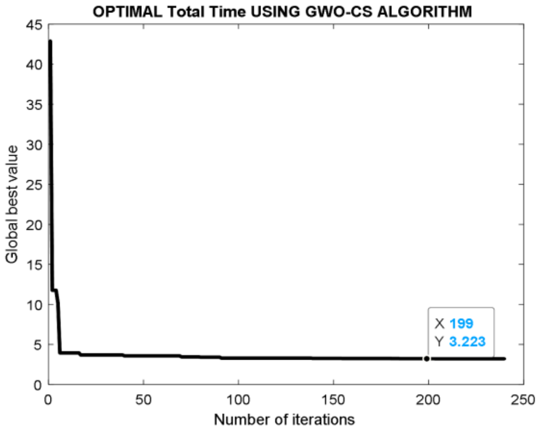

Figure 9. Convergence graph for 8 bus system

Table 8. Comparison of TMS

Relay number	GWO-CSA	Whale optimization algorithm (WOA)	Hybridized whale optimization algorithm (HWOA)
1	0.0526	0.1	0.1
2	0.0539	0.5929	0.5381
3	0.0537	0.1007	0.1
4	0.0511	0.1	0.2164
5	0.0517	0.3581	0.1
6	0.0998	0.249	0.2689
7	0.0476	0.1018	0.1
8	0.0407	0.343	1.1
9	0.0564	0.1	0.1
10	0.0477	0.1	0.1
11	0.054	0.1004	0.1
12	0.0543	0.1521	0.1
13	0.0499	0.1	0.1
14	0.0612	0.1	0.1

Table 9. Comparison of operating time

Methods	TOT in Seconds
GWO-CSA	3.221
WOA	5.95
HWOA	5.85

5. CONCLUSION

Relay coordination using hybrid optimization algorithm GWO-CSA is developed and results are observed for analysis. The convergence for the better TMS with the minimized total operating time is developed using MATLAB based implementation. The analysis for relay coordination with the constraint, without any constraint and with both constraint and DG is observed. The analysis developed on 8, 15, and 3 bus system inferred that the introduction of DG in the bus system improves the total operating time. The results obtained is satisfactory and is with par with the recent optimization algorithm recently implemented. The hybrid optimization of GWO-CSA method has shown good improvement than the recent optimization algorithms. To evaluate its efficacy and robustness the method can be applied further complex systems in the future implementations.

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