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Coordination of distance and directional overcurrent relays using a new algorithm: grey wolf optimizer

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Abstract: Optimal relay coordination has important effects on the stability, security, and reliability of a network. Hence, in this article, a method for optimal coordination of distance (D) and directional overcurrent (DOC) relays is presented. Taking into account the pickup current of the overcurrent relays as an optimization variable, in addition to the time setting multiplier (TSM) and the various characteristics of these relays, optimum and suitable settings for overcurrent and distance relays are obtained. The grey wolf optimizer algorithm has been used as an optimization tool to find optimum settings. The performance of this method has been investigated in 8-bus and 39-bus systems and compared with traditional GA and PSO algorithms. The results show that in the proposed method the operating times of the relays and the time interval between operating times of main and backup relays with respect to the coordination time interval have decreased.

Key words: Distance relay, directional overcurrent relay, grey wolf optimizer algorithm, pickup current, relay characteristic, optimization variables

1. Introduction

The purpose of a power system is to produce and supply stable electrical energy to consumers. The system should be designed to provide consumers with high reliability and economic energy. Electricity is produced at power plants and is delivered to the final consumers by means of transmission and subtransmission and distribution lines. Therefore, a wide range of protection and control devices for maintaining the system are considered. Most of these devices are based on digital technology, numerical calculations, and signal analysis. Among the most important of these devices are protective relays. The most important protective relays are used to protect subtransmission and some transmission lines, distance (D) and directional overcurrent (DOC) relays, whose coordination is important for the stability, security, and reliability of the network. Hence, various methods for coordination of relays were presented in previous published articles. For overcurrent relays, optimal coordination is performed using linear programming techniques including simplex [1], two-phase simplex [2], and duplex simplex [3].

In coordination problems, the goal is to minimize the discrimination time (time interval between operating times of main and backup relays with respect to the coordination time interval) between the main and backup relays, so the coordination issue can be considered as an optimization problem and can be solved using artificial intelligence methods. In these methods, the constraint coordination is involved in the objective function [4-7]. In [8] the optimal solution was created only by the constraints; the problem is that if the constraints are not

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satisfied, the optimal solution cannot be obtained. Optimal coordination was performed in [5,6] using a genetic algorithm and particle-swarm optimization method, respectively, while in [9] an evolutionary algorithm was implemented. Coordination in these methods has two problems. One of the issues is the lack of coordination and the absence of a solution for the relays with both continuous and discrete time setting multipliers. In [4] the mentioned problems were solved. The existing genetic algorithm was improved by adding a new expression to the objective function, so that the incompatibility problems were resolved. The coordination algorithm can also manage continuous and discrete time setting multipliers. In [10], the problem of optimal coordination of DOC relays was solved as a problem with nonlinear variables and with discrete variables (MINLP). In order to simplify this complex problem, in [11,12], considering constant current variables of the relays, this problem was solved as a linear problem. In [13], transient stability was added as a constraint to the issue of overcurrent relay coordination and the pattern search method was used to solve the optimization problem. In [14], an algorithm, i.e. hyperspherical search, was used for coordination of overcurrent relays with different relay characteristics. In [15], a mixed-integer linear programming method (MILP) for the coordination problem of DOC relays considering the pickup current as the discrete optimal variable and the time setting multiplier as the continuous optimal variable was presented. In this method the branch and bound solver for the coordination problem, which is a nonlinear and nonconvex problem, was used, making a linear and convex problem in each branch. It should be noted that in all of the above articles, optimal coordination was only performed for overcurrent relays, while in subtransmission and transmission lines, D and DOC relays are used simultaneously in protective schemes. Thus, these relays must be coordinated with each other.

In order to coordinate the D and DOC relays, a series of parameters including the time of operation of the second zone of the D relays (t_{z2}), the pickup current (I_{Pickup}), and the TSM of the overcurrent relays must be determined. The authors of [16] calculated the optimal value of the second zone of the D relays in a protective program combining with overcurrent relays. Also, in [16], a new objective function using a genetic algorithm was presented to solve the optimal coordination problem for overcurrent and D relays. The TSM and the characteristics of the overcurrent relays were selected, but the pickup currents of constant values were assumed. In [17], the D and DOC relay coordination problem with LP method was solved by considering t_{z2} and TSM as optimization variables. In this work, the optimal settings for the D relays taking into account equal values for the operating time of the second zone of all D relays were determined. In [18], the problem of the coordination of D and DOC relays was formulated in a network with a series compensator for transmission lines. This problem was solved using a modified adaptive PSO algorithm. Selectivity constraints were defined in this work at three critical points. One of the points was related to the coordination of overcurrent relays and the other two points related to the coordination of D and DOC relays. In [19], because of the characteristics of the various overcurrent relays used to set these relays, these characteristics and TSM were defined as problem variables while t_{z2} and I_{Pickup} definite values were assumed. In this work, by entering selectivity constraints in the objective function of the problem, a new objective function for the coordination problem was presented. In [20], the above-mentioned objective function was used for coordination, with the exception that the Sachedo characteristic is used for overcurrent relays and only the TSM as a variable of overcurrent relays in the optimization problem. The difficulty of [19,20] is that the overcurrent relay is assumed to be only a backup of the D relay, with the coordination of the D and DOC relays, taking into account one critical point, the end of the first zone of the D relay, and this false assumption has led to acceptable answers to the problem by setting t_{z2} with a classical value of 0.3 s.

In this article, by improving the objective function in the coordination problem, the effect of the pickup current as an optimization variable has been considered. Moreover, the grey wolf optimization algorithm (GWOA) as an optimization algorithm is used to find the best TSMs, the best characteristics of the overcurrent relays, and the pickup currents of the overcurrent relay. In order to consider all of the different modes in the coordination of the D and DOC relays, the objective function used in [16] has been considered. It is shown that the coordination has been improved using the proposed method. To show the GWOA's performance, it has been compared with conventional methods, i.e. the GA and PSO.

2. Optimization problem for the coordination of D and DOC relays

The optimization problem for the coordination of the D and DOC relays is the determination of the pickup current and TSM of the overcurrent relays and operating time of D's relay zone in such a way that:

1- There is no operation for any other relay except main and backup relay.

2- Detachment of the fault occurs as soon as possible from the main network.

It is assumed that the coordination of the D relays with other D relays has been done separately. In addition, settings of impedances and the operating time of the zones of the D relays are already calculated. The time of operation of the first, second, and third zones of the D relays is 0.01, 0.3, and 0.6, respectively. Due to the ability to set up overcurrent relays with different characteristics, we first define the characteristics of the overcurrent relay as discrete variables of the problem.

Other parameters that are involved in the adjustment and coordination are the pickup current and TSM. The relay pickup current is used for the sensitivity of the protective system to the faults in the protective zones and usually TSM is used for selecting the protective system by making the relay coordination. For overcurrent relays, first the pickup current is determined, and then TSM is calculated. However, in the optimal calculation of these coefficients, the algorithm can be used to calculate both pickup current and TSM to coordinate the main and backup relays. Because of the pickup current floating range due to the sensitivity of the protective system, the relay pickup current can be chosen so that the relay has better performance.

Four different coordination processes including main D relay-backup D relay, main DOC relay-backup DOC relay, main D relay-backup DOC relay, and main DOC relay-backup D relay should be considered. Coordination of main D relay-backup D relay must be performed before the start of the optimization process to calculate the setting of impedances of the different zones of the D relays.

In the next step, these settings are used in the optimization algorithm to coordinate the D and DOC relays. Therefore, the TSMs of all overcurrent relays and the operating time of the second zone of all of the D relays should be determined for critical conditions. Critical conditions for the coordination of main DOC-backup DOC in [16] are shown in Figure 1.

The discrimination times between operating time relays for faults at F1 (near end fault) and F2 (far end fault) should be checked as follows:

$$t_b(F1) - t_m(F1) \geq CTI_1, \tag{1}$$

$$t_b(F2) - t_m(F2) \geq CTI_1, \tag{2}$$

where $t_m(F_i)$ and $t_b(F_i)$ are the operating times of the main and backup DOC relays at critical points F1 and F2, and CTI_1 the coordination time interval for the coordination of DOC-DOC relays.

In the coordination of the D and DOC relays, the DOC relay is a backup for the D relay. Critical points are shown in Figure 2, when the fault occurs at F3 and F4, and the discrimination times between operating time of the backup DOC relay and the main D relay is minimized.

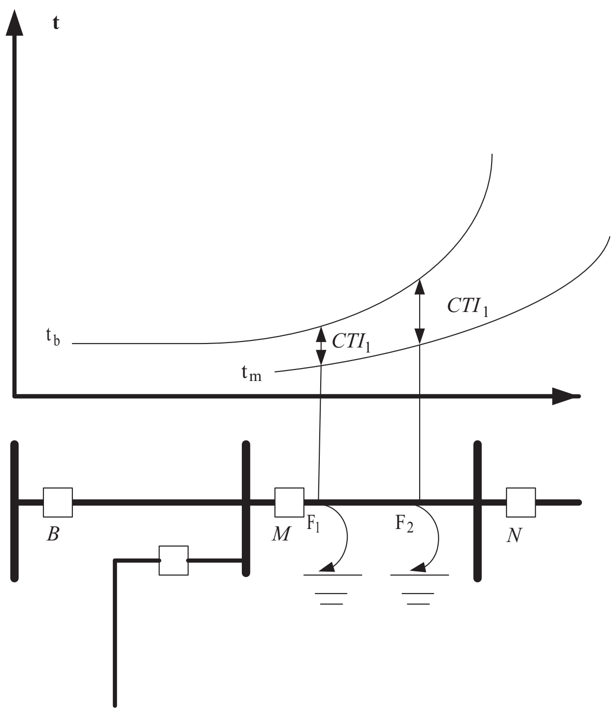

Figure 1. Critical conditions for the coordination between DOC relays.

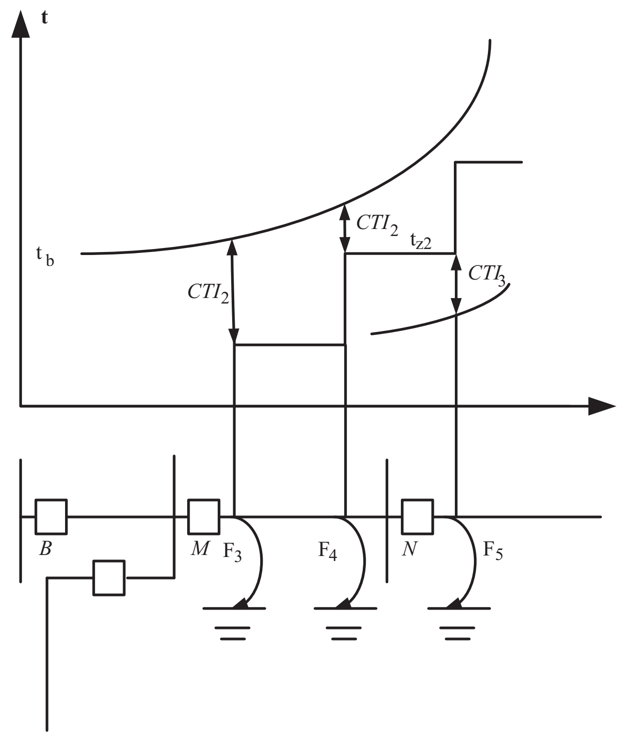

Figure 2. Critical conditions for the coordination between D and DOC relays.

Therefore, the following statements should be specified at the critical points of the fault F3 and F4:

$$t_b(F3) - t_{z1} \geq CTI_2, \tag{3}$$

$$t_b(F4) - t_{z2} \geq CTI_2, \tag{4}$$

where $t_b(F_i)$ is the operating time of the DOC relay in F_i, t_{z1} and t_{z2} is the operating time of the first and second zone of the D relay, and CTI_2 the coordination time interval for the coordination of the main D-backup DOC.

$$t_{z2} - t_m(F_5) \geq CTI_3, \tag{5}$$

where CTI_3 is the coordination time interval for coordination of main DOC-backup D relays. Other parameters are defined in the previous equations.

CTI_1, CTI_2, CTI_3 are assumed to be equal to 0.2. Eqs. (1) and (2) are given in the $O.F_{DOC-DOC}$ formula. $O.F_{DOC-DOC}$ is formulated as follows:

$$
\begin{aligned}
O.F_{DOC-DOC} =& \alpha \sum_{i=1}^{N} t_n + \beta_1 \\
& \times \sum_{k_1=1}^{p_1} (\Delta t_{mbDoc|F_1|} - |\Delta t_{mbDoc|F_1|}|) + \beta_1 \\
& \times \sum_{k_1=1}^{p_1} (\Delta t_{mbDoc|F_2|} - |\Delta t_{mbDoc|F_2|}|) + \beta_2 \\
& \times \sum_{k_1=1}^{p_1} (\Delta t_{mbDoc|F_1|} + |\Delta t_{mbDoc|F_1|}|) + \beta_3 \\
& \times \sum_{k_1=1}^{p_1} (\Delta t_{mbDoc|F_2|} + |\Delta t_{mbDoc|F_2|}|).
\end{aligned} \tag{6}
$$

$O.F_{DOC-D}$ guarantees the constraints of Eq. (3) and (4) and is formulated as follows:

$$
\begin{aligned}
O.F_{DOC-D} =& \beta_1 \times \sum_{k_1=1}^{p_2} (\Delta t_{mbDocD|F_3|} - |\Delta t_{mbDocD|F_3|}|) \\
& + \beta_1 \times \sum_{k_1=1}^{p_2} (\Delta t_{mbDocD|F_4|} - |\Delta t_{mbDocD|F_4|}|) \\
& + \beta_4 \times \sum_{k_1=1}^{p_2} (\Delta t_{mbDocD|F_3|} + |\Delta t_{mbDocD|F_3|}|) \\
& + \beta_5 \times \sum_{k_1=1}^{p_2} (\Delta t_{mbDocD|F_4|} + |\Delta t_{mbDocD|F_4|}|).
\end{aligned} \tag{7}
$$

The objective function of coordination when the D relay is the backup of the DOC relay is as follows:

$$
O.F_{D-DOC} = \beta_6 \times \sum_{k_1=1}^{p_3} (\Delta t_{mbDDoc}). \tag{8}
$$

The final objective function of the GWOA is obtained for coordination of DOC and D relays as follows:

$$
O.F = O.F_{DOC-DOC} + O.F_{DOC-D} + O.F_{D-DOC}, \tag{9}
$$

where $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$, and β_6 are the weight coefficients and k_1 is the number of main and backup DOC relay pairs, which changes from 1 to p_1, and k_2 is the number of main D and backup DOC relays, which changes from 1 to p_2, k_3 is the number of main DOC and backup D relays that changes from 1 to p_3, $\Delta t_{mbDoc|F_i|}$ is called the discrimination time between the main and backup DOC relays for the fault occurring at F_i, and $\Delta t_{mbDocD|F_i|}$ is the discrimination time between the main D and backup DOC relays for the fault at F_i, obtained from:

$$
\Delta t_{mbDoc|F_i|} = t_{bDoc|F_i|} + t_{mDoc|F_i|} - CTI_1, \tag{10}
$$

$$
\Delta t_{mbDocD|F_i|} = t_{bDoc|F_i|} + t_{mD|F_i|} - CTI_2, \tag{11}
$$

where $t_{bDoc|F_i|}$ and $t_{mDoc|F_i|}$ are the operating times of the main and backup DOC relays for the fault at F_i, respectively, and $t_{mD|F_i|}$ is the operating time of the first zone of the main D relay at F_i. $\Delta t_{mbDDoc|F_i|}$ is defined as follows and used in $O.F_{D-DOC}$ to decrease the operating time of the second zone of the D relay:

$$\Delta t_{mbDDoc} = t_{z2} - CTI_3, \tag{12}$$

where t_{z2} (the operating time of the second zone of the D relays) at each iteration of the GWOA is obtained according to Eq. (5) as follows:

$$t_{z2} = max((t_m(F_5) + CTI_3), t_z), \tag{13}$$

where t_z is the initial time delay for the second zone of the D relay. Now OF has been prepared for optimization by an optimization algorithm. The proposed objective function is selected in such a way that while observing the difference in operating time between the main and backup relays, the overall time of the operating of the two relays is also optimally put. For overcurrent relays, the operating time can be obtained from the following formula:

$$t = TSM(\frac{k}{M^{\alpha} - 1} + L), \tag{14}$$

where K, α, and$L$ are dependent on the relay characteristic obtained from Table 1 and M is the ratio of short-circuit current to pickup current:

$$M = \frac{I_{sc}}{I_{pickup}}. \tag{15}$$

I_{Pickup} can be obtained from the following formula:

$$I_{pickup} = I_P f \times I_{Laod}, \tag{16}$$

where I_{Load} is the load current and $I_p f$ is the pickup current factor. In this OF the upper and lower limits of pickup current are as follows:

$$I_P f_{min} \leq I_P f \leq I_P f_{max}, \tag{17}$$

where $I_p f_{min}$, $I_p f_{max}$ are considered in this article as 1 and 1.5, respectively. The same pickup current factor for all TSMs should be selected according to the following limitation:

$$TSM_{min} \leq TSM \leq TSM_{max}, \tag{18}$$

where TSM_{min} and TSM_{max} in this article are considered as 0.05 and 2, respectively. Other coefficients are as follows:

$$\alpha = 1, \beta_1 = 100, \beta_2 = \beta_3 = ... = \beta_6 = 2.$$

3. Grey wolf optimizer algorithm (GWOA)

The GWOA is a metaheuristic algorithm inspired by nature based on the hierarchical structure and social behavior of wolves at the time of hunting. The grey wolf is a Canadian wolf family. The GWOA is based on a population and has a simple process in settings and can be easily extended to large-scale issues. In this article, four types of grey wolves, alpha, beta, delta, and omega, have been used to simulate a hierarchy of leadership, in which the main steps of hunting, searching for prey, prey siege, and prey attack are simulated. The results are

Table 1. Characteristics of the overcurrent relays.

No. of characteristic	Type of characteristic	Standard	K factor	α factor	L factor
1	Short time inverse	Manufacturer (AREVA)	0.04	0.05	0
2	Standard inverse	IEC	0.14	0.02	0
3	Very inverse	IEC	13.5	1	0
4	Extremely inverse	IEC	80	2	0
5	Long time inverse	Manufacturer (AREVA)	120	1	0
6	Moderately inverse	ANSI/IEEE	0.0515	0.02	0.114
7	Very inverse	ANSI/IEEE	19.61	2	0.491
8	Extremely inverse	ANSI/IEEE	28.2	2	0.1217

compared with traditional methods such as the particle swarm optimization algorithm (PSO) and the genetic algorithm (GA) for the desired problem. These results show that the GWOA performs better.

First the pack locates the herd of prey and then surrounds them. Wolves prefer prey that is weak/sick/old or injured. Alpha, beta, and delta wolves locate the weakened prey through its body stance, uncoordinated movements, or the smell of wounds and start to chase it. Omegas follow the dominant wolves [21]. Grey wolves act as follows [22]:

- Tracing, chasing, and approaching the prey.
- Tracking, sieging, and harassing the prey until it stops.
- When the prey stops moving, the wolves create a rough polygon around the prey.
- Attacking the prey.

In this article, the hierarchical structure and the social behavior of the wolves during the hunting process are modeled mathematically and used to design an optimization algorithm. The model is presented in Figure 3.

4. Application of GWOA in solving optimal coordination problem

Many metaheuristic optimization techniques have been introduced in the last two decades. Metaheuristics are respected by researchers for their simplicity, flexibility, and escape of the local optimum, but according to the no free lunch (NFL) theory, it has been logically proven that no metaheuristics respond to all the optimization problems. In other words, a special metaheuristic may show promising results to solve a series of problems, but this algorithm may show poor performance for a number of other issues.

We have used the GWOA in this article, and as shown in the results section, the optimal setting for the relays in the optimal coordination problem has been obtained.

5. Optimization results and discussion

5.1. IEEE 8-bus network

In order to test the proposed method and compare it with the previous methods, the 8-bus system is first selected. This collection includes 8 buses, 7 lines, 2 generators, and 2 transformers (Figure 4). Details of the system were obtained from [18]. A total of 14 D relays and 14 DOC relays are used to protect lines, such that there are a D and a DOC relay in both ends of each line. The nominal and short-circuit currents passing through the relays for the 8-bus test system are obtained using DIGSILENT software. Due to the high amount of data, they have been discarded.

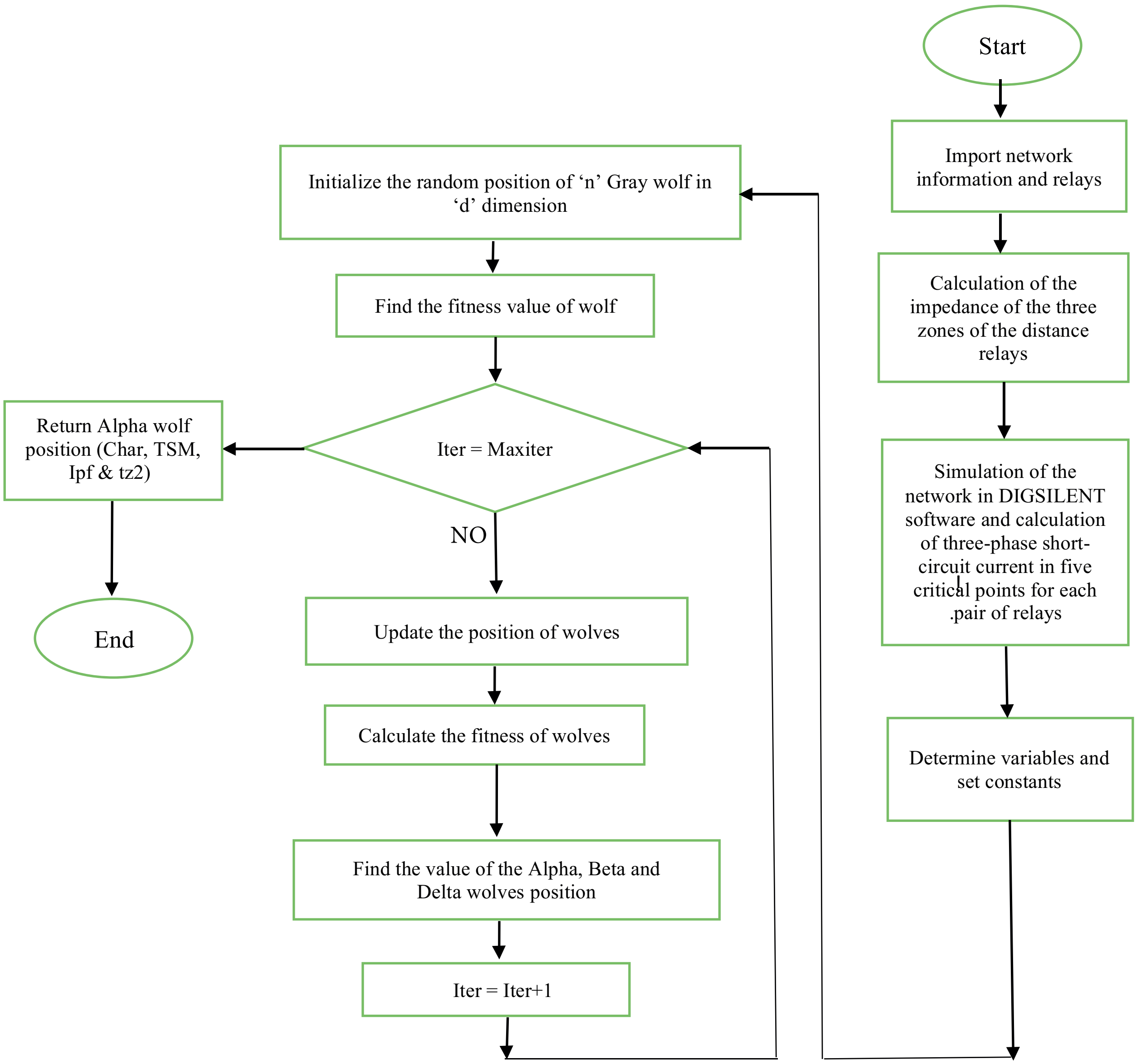

Figure 3. Proposed method.

To illustrate the advantage of considering the pickup current as an optimization variable as well as the efficiency of the proposed optimization algorithm, we consider the following three cases.

Case 1: TSM and the characteristic of the overcurrent relays as the optimization variables and I_Pf are fixed and equal to 1.20.

Case 2: TSM and I_Pf as the optimization variables and relay characteristics are fixed (standard inverse characteristic).

Case 3: TSM and I_Pf and characteristic of overcurrent relays as optimization variables (suitable case).

The output of the GWOA for different cases including $TSMs$, I_Pfs, and the characteristics of the overcurrent relays are given in Table 2. The pickup current of the overcurrent relays according to the pickup current factors is obtained from the optimization algorithm and given in Table 3. The operating times of the overcurrent relays

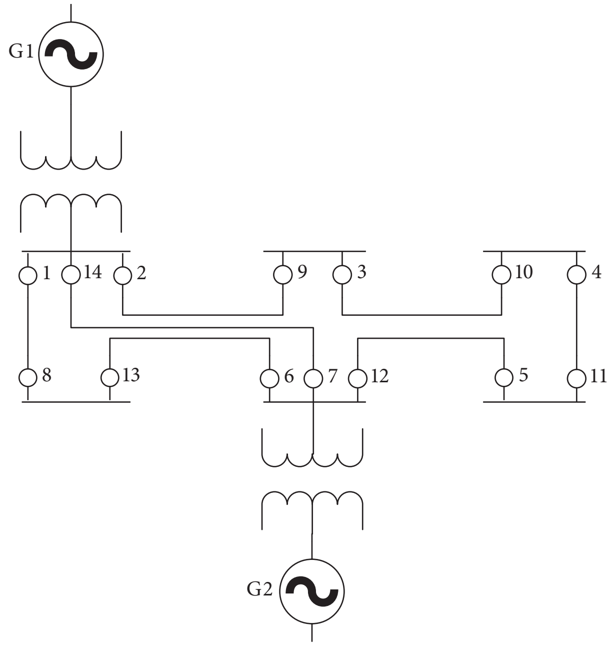

Figure 4. The 8-bus system.

(for the near end fault to the main relay) and the operating time of the second zone of the D relays for different cases are given in Table 4. The discrimination times (time interval between operating times of main and backup relays with respect to the coordination time interval) for critical points of DOC relays, backup of DOC relays and DOC relays, and backup of D relays are given in Table 5.

Table 2. GWOA output (TSM, I_Pf, relay characteristic).

Relay no.	TSM			I_Pf			No. of selected characteristic		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
1	0.21	0.30	0.28	1.20	1.90	1.90	3	2	3
2	0.71	0.32	0.36	1.20	1.00	1.12	3	2	3
3	0.19	0.27	0.84	1.20	1.00	1.05	2	2	4
4	0.10	0.17	0.27	1.20	1.03	1.05	2	2	7
5	0.07	0.13	0.12	1.20	1.00	1.03	3	2	7
6	0.60	0.36	0.73	1.20	1.21	1.00	3	2	3
7	0.17	0.28	0.69	1.20	1.00	1.01	2	2	1
8	0.86	0.35	0.53	1.20	1.03	1.07	3	2	3
9	0.12	0.15	0.23	1.20	1.08	1.05	7	2	6
10	0.55	0.22	0.33	1.20	1.04	1.00	8	2	3
11	0.94	0.28	0.42	1.20	1.04	1.7	4	2	3
12	0.64	0.39	0.78	1.20	1.00	1.18	3	2	3
13	0.47	0.26	0.21	1.20	1.00	1.01	6	2	3
14	0.70	0.28	0.84	1.20	1.01	1.02	1	2	1
Avg. value	0.45	0.27	0.47	1.20	1.04	1.06	-	-	-

Table 3. Pickup current of the overcurrent relays.

Relay no.	Load current	Case 1	Case 2	Case 3	Relay no.	Load current	Case 1	Case 2	Case 3
1	104	125.00	113.36	113.36	8	109	131.00	112.27	116.63
2	106	200.00	166.00	185.92	9	118	142.00	127.44	123.90
3	125	150.00	125.00	131.25	10	110	132.00	137.28	110.00
4	180	216.00	185.40	189.00	11	135	162.00	140.40	157.95
5	129	155.00	128.00	132.87	12	122	146.00	122.00	143.96
6	114	137.00	137.94	114.00	13	125	150.00	125.00	126.25
7	141	169.00	141.00	142.41	14	166	200.00	167.66	169.32

Table 4. GWOA output (t_{op}, t_{z2}).

Relay no.	t_{z2}			t_{op}		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
1	0.70	1.05	0.64	0.14	0.64	0.16
2	0.67	0.82	0.40	0.36	0.63	0.17
3	0.55	0.75	0.41	0.40	0.55	0.09
4	0.45	0.73	0.33	0.32	0.52	0.19
5	0.60	0.99	0.57	0.15	0.43	0.09
6	0.42	0.95	0.47	0.23	0.69	0.23
7	0.70	0.89	0.44	0.36	0.56	0.23
8	0.74	0.89	0.43	0.31	0.63	0.17
9	0.73	1.05	0.64	0.09	0.45	0.28
10	0.32	0.72	0.52	0.10	0.49	0.19
11	0.36	0.76	0.50	0.15	0.59	0.25
12	0.41	0.82	0.50	0.24	0.69	0.28
13	0.59	0.94	0.58	0.47	0.60	0.15
14	0.52	0.96	0.57	0.27	0.59	0.30
Avg.	0.55	0.88	0.50	0.25	0.58	0.19

As is clear from the results, in the proposed method, the best case is taken when the TSM, I_Pf, and characteristic of the overcurrent relays are considered as the optimization variables (third case). In this case there is no miscoordination and the operating times of the backup DOC relays are relatively small. Also, the operating times of the D and DOC relays are smaller than the results of previous methods. Therefore, it is shown that the use of the GWOA considering TSM, I_Pf, and the characteristic of overcurrent relays as optimization variables is effective.

To illustrate the efficiency of the GWOA, we compared the results with traditional algorithms such as the GA and PSO for solving the optimal coordination problem for the combination of D and DOC relays.

Case A: GA
Case B: PSO
In both cases, TSM, I_Pf, and the characteristics of the overcurrent relays are considered as optimization variables. The output of the GA and PSO algorithms is shown in Table 6 and Table 7 for solving the optimal coordination problem for the combination of D and DOC relays. Also, in Table 8, the discrimination times for

Table 5. GWOA output (discrimination times for the critical fault point).

Main relay	Backup relay	Case 1				Case 2				Case 3			
		Δt_{mbDoc}		Δt_{mbDocD}		Δt_{mbDoc}		Δt_{mbDocD}		Δt_{mbDoc}		Δt_{mbDocD}	
		F1	F2	F3	F4	F1	F2	F3	F4	F1	F2	F3	F4
2	1	0.5	0.6	0.7	0.8	0.9	1.1	1.2	1.2	1.3	1.2	1.2	1.2
14	1	0.04	0.06	0.29	0.47	0.25	0.00	0.82	0.91	0.10	0.00	0.39	0.64
3	2	0.00	0.48	0.35	0.52	0.00	3	0.49	0.36	0.00	0.00	0.05	0.00
4	3	0.00	0.03	0.30	0.11	0.00	0.00	0.47	0.30	0.00	0.46	0.15	0.26
5	4	0.07	0.47	0.20	0.29	0.04	0.73	0.43	0.64	0.00	1.59	0.07	0.44
6	5	0.36	-	0.56	0.00	0.05	-	0.70	0.00	0.05	-	0.26	0.00
7	5	0.24	0.09	0.58	2.60	0.18	0.00	0.71	1.52	0.05	0.00	0.27	1.35
1	6	0.10	0.86	0.21	0.52	0.00	0.14	0.60	0.63	0.07	0.74	0.21	0.52
2	7	0.00	0.03	0.31	0.22	0.00	0.26	0.57	0.56	0.00	0.04	0.12	0.00
8	7	0.00	-	0.31	3.59	0.00	-	0.57	3.63	0.00	-	0.12	1.35
13	8	0.00	1.16	0.42	0.94	0.00	0.05	0.54	0.51	0.00	0.45	0.13	0.28
8	9	0.04	-	0.33	0.00	0.24	-	0.83	0.00	0.24	-	0.38	0.00
14	9	0.09	0.00	0.34	1.83	0.28	0.02	0.84	1.76	0.11	0.00	0.39	0.73
9	10	0.00	1.85	0.04	0.57	0.00	0.13	0.42	0.48	0.00	1.22	0.24	0.65
10	11	0.00	0.94	0.07	0.45	0.00	0.05	0.43	0.32	0.00	0.21	0.14	0.20
11	12	0.01	0.02	0.14	0.00	0.00	0.01	0.55	0.34	0.00	0.05	0.21	0.07
7	13	0.20	0.04	0.53	0.57	0.19	0.00	0.73	0.81	0.08	0.00	0.30	0.49
12	13	0.31	0.66	0.53	0.57	0.05	0.50	0.72	0.82	0.02	0.58	0.29	0.50
6	14	0.00	-	0.19	1.07	0.00	-	0.63	2.19	0.02	-	0.23	0.95
12	14	0.00	0.05	0.19	0.05	0.00	0.26	0.63	0.63	0.00	0.03	0.23	0.10
Avg. value		0.08	0.37	0.31	0.75	0.07	0.15	0.62	0.87	0.05	0.32	0.23	0.46

the critical fault point for the GA, PSO, and GWOA (case 3), i.e. TSM, I_Pf, and the characteristics of the overcurrent relays, are considered as optimization variables.

As seen in various cases (Case 1, Case 2, Case 3, Case A, Case B), the smaller TSM of the overcurrent relays is not due to the low operating time of the relays. It is also clear from the outputs of the GA and PSO algorithms that suitable coordination for D and DOC relays has been obtained by using these algorithms. At the same time, the performance of the GWOA is better both in terms of the operating time of the relays and in terms of the discrimination times. In fact, using this algorithm, there are smaller positive discrimination times, which indicates better coordination between the D and DOC relays.

5.2. 39-Bus system

In order to demonstrate the efficiency of the proposed method, this method is implemented on the 39-bus system, i.e. a 345-kV transmission system that has 34 transmission lines, 12 transformers, and 10 generators. The network consists of 136 relays (68 D relays + 68 DOC relays). Details of the system were obtained from [23]. The nominal and short-circuit currents passing through relays for the 39-bus test are obtained using DIGSILENT software. Due to the high amount of data, they have been discarded.

Table 6. GA and PSO outputs (TSM, $I_P f$, $RelayChar.$).

Relay no.	TSM		$I_P f$		No of selected characteristic	
	Case A	Case B	Case A	Case B	Case A	Case B
1	0.30	0.05	1.00	1.00	3	5
2	0.66	0.61	1.00	1.10	3	3
3	0.54	0.35	1.00	1.36	3	3
4	0.31	0.13	1.00	1.19	6	3
5	0.09	0.08	1.00	1.00	2	2
6	0.50	0.06	1.15	1.34	3	5
7	0.16	0.37	1.00	1.00	2	6
8	1.12	0.58	1.17	1.05	4	3
9	0.23	0.32	1.00	1.00	6	4
10	0.65	0.40	1.00	1.04	4	3
11	1.05	0.60	1.08	1.00	4	3
12	0.59	0.27	1.30	1.02	3	2
13	0.33	0.28	1.00	1.00	4	3
14	0.34	0.22	1.00	1.00	6	2
Avg. value	0.49	0.31	1.05	1.07	-	-

Table 7. GA and PSO outputs (t_{op}, t_{z2}).

Relay no.	t_{z2}		t_{op}	
	Case A	Case B	Case A	Case B
1	0.62	0.86	0.16	0.24
2	0.61	0.57	0.28	0.26
3	0.61	0.50	0.27	0.24
4	0.56	0.53	0.38	0.25
5	0.56	0.56	0.29	0.26
6	0.47	0.59	0.18	0.23
7	0.58	0.56	0.32	0.31
8	0.37	0.51	0.06	0.19
9	0.62	0.86	0.28	0.39
10	0.52	0.65	0.10	0.25
11	0.42	0.59	0.13	0.31
12	0.39	0.57	0.24	0.49
13	0.55	0.73	0.07	0.20
14	0.32	0.73	0.30	0.45
Avg.	0.51	0.63	0.22	0.29

The proposed method in the 39-bus system with different cases is same as for the 8-bus system for the relay coordination problem.

A summary of the discrimination times between pairs of main and backup relays for the different cases obtained from the GWOA is given in Table 9.

Table 8. GA, PSO, and GWOA outputs (discrimination times for the critical fault point).

Main relay	Backup relay	Case A (GA)				Case B (PSO)				Case 3 (GWOA)			
		Δt_{mbDoc}		Δt_{mbDocD}		Δt_{mbDoc}		Δt_{mbDocD}		Δt_{mbDoc}		Δt_{mbDocD}	
		F1	F2	F3	F4	F1	F2	F3	F4	F1	F2	F3	F4
2	1	0.10	0.86	0.37	0.70	0.40	1.60	0.64	1.28	0.23	1.10	0.38	0.75
14	1	0.09	0.00	0.37	0.60	0.22	0.01	0.66	1.13	0.10	0.00	0.39	0.64
3	2	0.00	0.16	0.22	0.28	0.00	0.16	0.19	0.23	0.00	0.00	0.05	0.00
4	3	0.00	0.25	0.33	0.32	0.06	0.23	0.28	0.25	0.00	0.46	0.15	0.26
5	4	0.00	0.40	0.25	0.29	0.00	1.94	0.20	0.73	0.00	1.59	0.07	0.44
6	5	0.26	-	0.43	0.00	0.14	-	0.35	0.00	0.05	-	0.26	0.00
7	5	0.13	0.00	0.43	0.90	0.06	0.00	0.36	0.74	0.05	0.00	0.27	1.35
1	6	0.00	0.46	0.12	0.31	0.00	0.54	0.21	0.53	0.07	0.74	0.21	0.52
2	7	0.00	0.04	0.24	0.12	0.00	0.00	0.21	0.06	0.00	0.04	0.12	0.00
8	7	0.20	-	0.24	1.90	0.04	-	0.21	1.55	0.00	-	0.12	1.35
13	8	0.00	1.30	0.02	0.57	0.00	0.37	0.16	0.34	0.00	0.45	0.13	0.28
8	9	0.32	-	0.37	0.00	0.42	-	0.59	0.00	0.24	-	0.38	0.00
14	9	0.09	0.00	0.37	0.63	0.15	0.00	0.59	1.06	0.11	0.00	0.39	0.73
9	10	0.00	4.74	0.24	1.78	0.00	1.59	0.36	0.97	0.00	1.22	0.24	0.65
10	11	0.00	0.63	0.05	0.36	0.00	0.26	0.23	0.33	0.00	0.21	0.14	0.20
11	12	0.03	0.06	0.15	0.00	0.03	0.00	0.32	0.09	0.00	0.05	0.21	0.07
7	13	0.10	0.00	0.41	1.34	0.17	0.06	0.46	0.80	0.08	0.00	0.30	0.49
12	13	0.17	1.97	0.39	1.36	0.00	0.86	0.45	0.81	0.02	0.58	0.29	0.50
6	14	0.04	-	0.20	0.74	0.24	-	0.45	1.59	0.02	-	0.23	0.95
12	14	0.00	0.03	0.20	0.05	0.00	0.23	0.45	0.38	0.00	0.03	0.23	0.10
Avg. value		0.08	0.55	0.27	0.61	0.10	0.39	0.37	0.64	0.05	0.32	0.23	0.46

As shown in Table 9, simultaneous consideration of the TSM, pickup current factor, and characteristic of the overcurrent relays as optimization variables resulted in smaller discrimination times and moreover the rate of miscoordination was reduced. Therefore, the efficiency of the GWOA for solving the optimal coordination problem for the combination of D and DOC relays in practical power systems has been proved.

Table 9. Summary of discrimination times for GWOA outputs.

Δt	Case 1 Average of positive values(s)	Case 2 Average of positive values(s)	Case 3 Average of positive values(s)
$\Delta t_{mbDoc,F_1}$	0.44	0.39	0.18
$\Delta t_{mbDoc,F_2}$	1.36	1.20	1.06
$\Delta t_{mbDocD,F_3}$	0.89	1.46	0.62
$\Delta t_{mbDocD,F_4}$	1.37	1.76	0.83
Total	4.07	4.82	2.71
No. of miscoordination	40	34	31

6. Conclusion

In this article, by improving the objective function in the coordination problem, the effect of the pickup current as an optimization variable has been considered. Moreover, a new approach based on the GWOA as an optimization algorithm is used to find the best TSMs, characteristics, and pickup currents of overcurrent relays. The average operating time of distance and overcurrent relays and also the discrimination times have been decreased. The proposed approach is applied to two test systems, i.e. small and large (subtransmission and transmission voltage level), and also, it is compared with some previous approaches, i.e. the GA and PSO. The simulation results reveal that better coordination is obtained using the proposed method.

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