J Electr Eng Technol.2018; 13(3): 1043-1051
http://doi.org/10.5370/JEET.2018.13.3.1043

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Gray Wolf Optimizer for the Optimal Coordination of Directional Overcurrent Relay

Chang-Hwan Kim*, Tahir Khurshaid*, Abdul Wadood*, Saeid Gholami Farkoush* and Sang-Bong Rhee†

Abstract – The coordination of directional overcurrent relay (DOCR) is employed in this work, considering gray wolf optimizer (GWO), a recently designed optimizer that employs the hunting and leadership attitude of gray wolves for searching a global optimum. In power system protection coordination problem, the objective function to be optimized is the sum of operating time of all the main relays. The coordination of directional overcurrent relays is formulated as a linear programming problem. The proposed optimization technique aims to minimize the time dial settings (TDS) of the relays. The calculation of the Time Dial Setting (TDS) setting of the relays is the core of the coordination study. In this article two case studies of IEEE 6-bus system and IEEE 30-bus system are utilized to see the efficiency of this algorithm and the results had been compared with the other algorithms available in the reference and it was observed that the proposed scheme is quite competent for dealing with such problems. From analyzing the obtained results, it has been found that the GWO approach provides the most globally optimum solution at a faster convergence speed. GWO has achieved a lot of relaxation due to its easy implementation, modesty and robustness. MATLAB computer programming has been applied to see the effectiveness of this algorithm.

Keywords: Directional overcurrent relay, Gray wolf optimizer, Meta-heuristic technique, Optimal coordination, Power system protection, Time dial settings.

1. Introduction

In an interconnected electrical power system there arises so many nonlinear conditions that can affect the power system to operate linearly. The conditions that take place regularly during abnormalities are faults, overloading's, frequency mis-match, short circuits etc. These conditions will lead to interruption of supply and can damage the devices connected in an electrical power system. In order to get rid of those abnormalities there appears the significance of maintaining a reliable protective power system. For maintaining the safe and reliable protection, there should be secondary or back-up protection if the primary protection scheme fails. This will only lead into existence if and only if the main line of defense got some problems or if the primary protection scheme fails. Strictly speaking, operating after a time delay called as coordination time interval (CTI) or coordination time delay, giving a sheen for the main/ primary scheme to operate. The aforementioned gives priority to protective relaying coordination that comprises the selection for a proper setting to each relay such that their major protective task greets the existing schemes of protective relaying, namely reliability, speed, sensitivity and selectivity [1].

† Corresponding Author: Dept. of Electrical Engineering, Yeungnam University, Korea. (rrsd@yu.ac.kr)
* Dept. of Electrical Engineering, Yeungnam University, Korea. ({kranz , tahir, wadood, saeid_gholami}@ynu.ac.kr)
Received: September 7, 2017; Accepted: December 15, 2017

In the past decapod, trial and error approach was used for the coordination process of directional overcurrent relays (DOCR) and other relays in an interconnected power market utilizing digital computers. Conventionally, it experiences a slow rate of convergence because of vast number of iterations desired to swing suitable relay settings. The time dial settings of the relays are very high, it is important to make these settings optimum. In a trial and error approach to decrease the minimum amount of iterations necessary for the coordination procedure, a method to break all the loops called as "break points" and put the relays at the positions has been suggested [2-4], this technique on implementing had been found not to be optimal. The values of TDS have been found using simplex method for a given settings of pick-up current (I_p). In the era of 1988, the coordination of DOCR for optimization has been reported [5]. Recently optimization techniques like Genetic algorithm, evolutionary algorithm, [6, 7] had found a great interest and is used in the literature survey to find the optimum solution of the protective relays.

A new evolutionary meta-heuristic computation technique was proposed by Mirjalili et al, in 2014 [8, 9], named as Gray Wolf Optimizer (GWO). GWO is a new artificial intelligence technique that depends on the leadership and hunting behavior of wolves [10, 11] used to solve the optimization problems like artificial neural network training [12-14] and minimization of an objective function [15, 16]. GWO due to its superiority to spare evolutionary algorithms with reference to time and memory gained lot of interest to power system engineers, as it confides easy and simple mathematical operations and it craves slight lines of programming code to implement [17].

This paper describes the elucidation for the coordination problem of DOCR by using the GWO methodology. The improvement and implementation of this algorithm has been tested on 6-bus system and 30-bus system.

2. Coordination Problem Formulation

In DOCR coordination problems the objective function to be optimized for the sum of operating times of all the relays attached to the electrical power system, subject to the following constraints [18].

2.1 Coordination criteria

The two protective schemes i.e., the main and the backup protection scheme should be coordinated together by coordination time interval (CTI). The CTI for the electromechanically relays had been set to 0.3 to 0.4s and for the digital or microprocessor based relays is 0.1 to 0.2s. The above footing can be written as

$$T_b \geq T_p + CTI \tag{1}$$

Where T_b is the backup relay operating time. T_p is the primary (or main) relay operating time.

2.2 Operational characteristics of relay

Inverse overcurrent relay (OCR) comprises of two units, an instantaneous unit and a time dependent unit. The time dependent units have the two main values to fix that are pickup current value (I_p) and TDS. The pickup value is the minimum value of the operating current for which the relay operates and the TDS defines the operating time 'T' of the device for every current value [19-23]. The characteristics of DOCR has been given as the curve of T versus M, where M stands for multiple of pickup current and is explained as the ratio of relay current 'I_R' to the pickup current 'I_P'.

$$M = \frac{I_R}{I_P} \tag{2}$$

From manufacturer point of view, this ratio provides the current-time curve characteristics to characterize the operation of the electromechanical relays [20]. In this paper the inverse OCR characteristics is presented in (3) and (4).

$$T = k\frac{TDS}{M^{k_1} + k_2} \tag{3}$$

$$T = PTDS \times PI_P \tag{4}$$

where

$$PTDS = a_0 + a_1(TDS) + a_2(TDS)^2 + a_3(TDS)^3 \tag{5}$$

$$PI_P = b_0 + \frac{b_1}{(M-1)} + \frac{b_2}{(M-1)^2} + \frac{b_3}{(M-1)^3} + \frac{b_4}{(M-1)^4} \tag{6}$$

Where k, k_1, k_2, a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3 and b_4 are constants and depends upon the type of relay to be simulated.

2.3 Relay setting bound

The DOCR coordination study has the aspect to calculate the TDS and I_P. The constraints applied in this study allow continuous time dial settings in respect of pickup current settings. The constraints are:

$$TDS_{j\min} \leq TDS_j \leq TDS_{j\max} \tag{7}$$

$$I_{Pj\min} \leq I_{Pj} \leq I_{Pj\max} \tag{8}$$

This problem can be summarized mathematically, as shown in (9)

$$\min \sum_i \sum_j T_{ijprimary} \tag{9}$$

Where $T_{ij_{primary}}$ is the operating time of primary relay j for a fault i, subject to following constraints:

$$L(T) \leq 0\,(cordination\ criteria) \tag{10}$$

$$T = g(S)\,(relay\,characteristics) \tag{11}$$

$$S_{j\min} \leq S_j \leq S_{j\max}\ (Bounds\,on\,relay\ settings) \tag{12}$$

Where $L(T)$ is the coordination criteria represented by (1). S is the set of feasible settings used in TDS and I_p. $g(S)$ is the relay characteristics shown by (3) and (4).

In order to calculate the values of TDS for a given I_P, the pickup current values should be known. For a predefined I_P, equation (4) is reduced to

$$T = b \times TDS \tag{13}$$

where

$$b = \frac{k}{M^{k_1} + k_2} \tag{14}$$

Hence, the problem has been minimized to LP problem. In this case the problem is solved as the LP one to solve the problem without taking into consideration as LP one. Therefore, the corresponding TDS values could be found by calculating the roots of the polynomials as represented in (5) by employing the optimum values of polynomial time dial setting (PTDS) calculated.

This paper presents, GWO used to minimize the TDS of the relays for a given I_P. The coordination problem has been compared with the previously published results. The GWO has the capability of locating both linear and nonlinear optimization issues.

3. Gray Wolf Optimizer

Optimization technique came into existence during the world war second where the chief of the army said to his soldiers that we had to win this war without losses i.e., less economy and no casualties. So, optimization gave its birth where the objective function was winning a war subject to minimum losses (constraints). GWO is an efficient and promising newly developed meta-heuristic optimization technique used for non-convex optimization problems. It was first proposed by Mirjalili et al, in 2014 [8]. It is a population based optimization algorithm which is motivated by leadership and hunting behavior of Gray wolf. In nature, gray wolf (Canis lupus) correlates to Canidae family. It is considered to be residing at the top in the food chain and at a top level of predators. Gray wolves live in a truss which consists of 5-12 members on an average. In the group, strict dominant hierarchy is practiced, the leader of the folk is Alpha followed by Beta. The lowest rank in this optimization technique is Omega. If the wolf is not Alpha, Beta or Omega then it is called as Delta. In the GWO the best solution is Alpha followed by second best solution Beta followed by third best solution Delta. The rest of the solutions is considered as Omega. The Omega wolves just follow these three wolves [9]. There arises a common question that why meta-heuristics techniques have become so popular. The solution to this question can be categorized into the following facts: local optima avoidance, flexibility, derivation-free mechanism and simplicity. Fig. 1 depicts the hierarchy diagram of the gray wolves.

The social hierarchy consists of four levels that means Hierarchy exists in pack, α is the leader and decision maker, β and δ assist α in decision making, Rest of wolves ω are followers. The procedure for GWO technique are social hierarchy, tracking, encircling and attacking prey [10]. Gray wolf optimization has merits, it is easy to implement due its cinch structure; it takes less memory compared to other techniques; the convergence rate of this algorithm is faster because of the continuous reduction of search space and the judgment variables are less (α, β, δ); the main advantage of this algorithm is that it evades the local optima when applied to composite functions and only two parameters need to be adjusted (a & c). The only disadvantage of this optimization technique is that, in case of unimodel problems, initially it hastens towards the optimal solution starts slow down soon due to diversity problems.

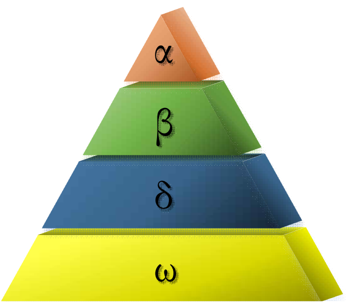

Fig. 1. Hierarchy of gray

3.1 Mathematical modeling of GWO

The hunt is generally assisted by alpha. Delta and beta sometime might take part in the hunt but occasionally. In order to mathematically mimic the hunting behavior of grey wolves, the first three best solutions (alpha, beta, and delta) obtained so far are saved and the other search agents (omega) are obliged to update their positions according and the updated position of the wolfs are shown in the Fig. 2. The blue, green, brown and yellow point shows the current position of the alpha, beta, delta and omega and the red depicts the estimated position of the prey.

In GWO modeling the fittest solution is considered as Alpha chased by second and third best solutions beta and delta respectively. The rest of the wolves are considered as omega. Grey wolves have adopted the hunting mechanism is escorted by α, β and δ while the remaining are ω wolves they just follow them [11].

When the wolves are in the mood of hunting the prey, they just encircle the prey which is given by the following equation:

$$E = \left| \vec{C} \cdot \vec{Z_P}(t) - \vec{Z}(t) \right| \tag{15}$$

$$\vec{Z}(t+1) = \vec{Z_P}(t) - \vec{A} \cdot \vec{D} \tag{16}$$

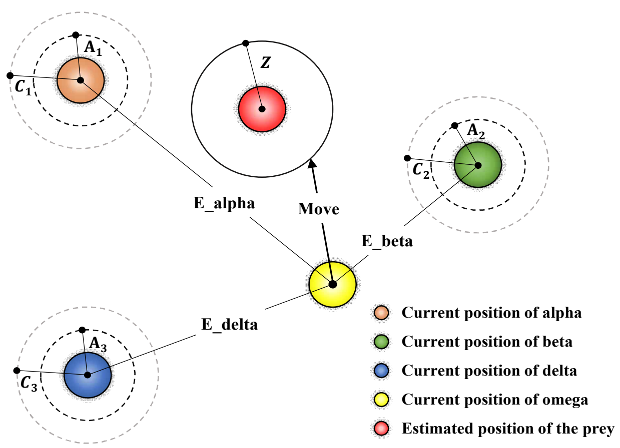

Fig. 2. Movement of gray wolf position

Where t is the current iteration, $\vec{Z}$ is the position vector of grey wolf, $\vec{Z_p}$ is the prey position, $\vec{A}$ and $\vec{C}$ are coefficient vectors and they had been calculated using the following equations:

$$\vec{A} = 2\vec{a}\cdot\vec{r_1} - \vec{a} \tag{17}$$

$$\vec{C} = 2\cdot\vec{r_2} \tag{18}$$

Where r_1 and r_2 are the random vectors between 0 and 1 and $\vec{a}$ is set to decrease from 2 to 0 during the course of iterations. The best three solutions have been saved and the other agents like omega wolves start updating their positions proceeding to their previous best position. These conditions had been shown by the following equations:

$$\vec{E_\alpha} = \left|\vec{C_1}\cdot\vec{Z_\alpha} - \vec{Z}\right|,\quad \vec{E_\beta} = \left|\vec{C_2}\cdot\vec{Z_\beta} - \vec{Z}\right|,\quad \vec{E_\delta} = \left|\vec{C_3}\cdot\vec{Z_\delta} - \vec{Z}\right| \tag{19}$$

$$\vec{Z_1} = \vec{Z_\alpha} - \vec{A_1}\cdot(\vec{Z_\alpha}), \vec{Z_2} = \vec{Z_\beta} - \vec{A_2}\cdot(\vec{Z_\beta}), \vec{Z_3} = \vec{Z_\delta} - \vec{A_3}\cdot(\vec{Z_\delta}) \tag{20}$$

$$\vec{Z}(t+1) = \frac{\vec{Z_1} + \vec{Z_2} + \vec{Z_3}}{3} \tag{21}$$

To entirety up, the advancement approach for GWO is beginning with making an arbitrary populace of gray wolves which can be called as candidates of the solution. Amid the recreation, alpha, beta and delta wolves appraise the conceivable position of the prey. The parameter of $\vec{a}$ in (17) can be displayed as exploration and exploitation forms by diminishing the incentive from 2 to 0. Candidate solutions are wandered from the prey if $|A| > 1$ and united toward the prey if $|A| < 1$. At long last GWO calculation is ended by the rule that has been set at first.

4. Objective Function Used During the Implementation

Objective function is the heart of every optimization technique; different categories of the objective function have been used for the coordination problem in the literature. In this research work the objective function to be minimized is the sum of operating times of main (primary) relays as shown in (9). Equation (9) has the objective of minimizing the stress on the relays.

There is no support in limiting the operating times of the relays when working as main relays over limiting their operating times when working as backup relays. The reason for this is for a given relay, if its main working time is limited, then its working time when operating as a backup relay is likewise limited. As it were, the working time of the primary relay and those of the backup relays are not in strife at the point when considered as independent targets, and in this way a lessening of one leads fundamentally to the lessening of the other [5]. The implementation of GWO for solving the coordination problem of DOCR is depicted in Fig. 3.

As specified some time recently, the coordination issue is tackled in terms of TDS, given that IP estimations of all the relays are predefined [24-29]. The objective function is to minimize the total operating time of primary relays. Keeping in mind the end goal to take care of the coordination issue regarding TDS, the relay attributes given by (3) or (4) ought to be utilized. For predefined I_P estimations of all relays, the target work given by (9) swings to:

$$\min \sum_{j=1}^{n} b_j \times TDS_j \tag{22}$$

Where 'n' is the number of relays to be set, b_j is the coefficient of j^{th} relay by (14).

It ought to be noticed that because of the specific attributes of the scientific detailing of the optimization issue, the arrangement is free on the estimations of the coefficients of the TDS factors, the length of they are certain genuine numbers. Appropriately, (22), is lessened to:

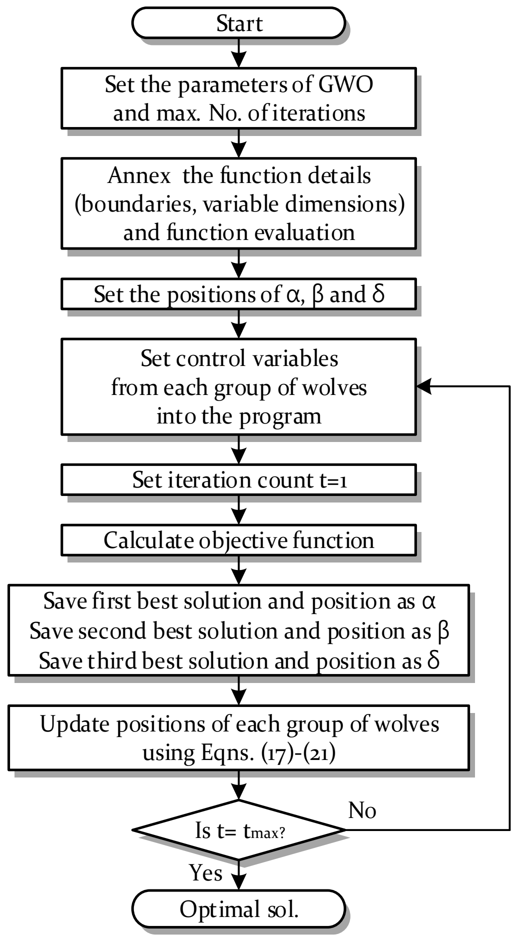

Fig. 3. Flow Chart of GWO

Table 1. GWO parameters used during the simulation

Parameter	Values
Population Size	10
No. of iterations	50
a	[0, 2]
R_1 and r_2	[0, 1]

$$\min \sum_{j=1}^{n} TDS_j \tag{23}$$

This objective function is subjected to the following constraints:

$$g(TDS_b) - g(TDS_p) \geq CTI \tag{24}$$

$$TDS_{j\min} \leq TDS_j \leq TDS_{j\max} \tag{25}$$

Where $g(\mathrm{TDS_b})$ back-up relay operating time as a function of TDS, $g(TDS_p)$ main relay operating time as a function of TDS. $\mathrm{TDS}_{j_{\min}}$ and $TDS_{j_{\max}}$ are the minimum and maximum allowable TDS of the j^{th} relay.

The GWO parameters used during the course of simulation are summarized in Table 1. Table 1 shows that the population size used during simulation is ten agents, which is very little size as compared to previously published literature. In addition of r_1 and r_2 are set between 0 and 1.

5. Result and Discussion

The proposed algorithm used to coordinate the DOCR has been verified on two case studies IEEE 6-bus system and IEEE 30-bus system and the results had been obtained using MATLAB.

5.1 IEEE 6-bus system

The single-line diagram of IEEE 6-bus system is shown in Fig. 4 which consists of four power generators, seven lines and fourteen directional overcurrent relays. The objective of the optimization technique in this case is to coordinate the settings of fourteen relays and the main aim of the proposed technique is to find out the optimal value of TDS.

At the near-end of each relay (close in faults) three phase faults are applied. The primary/backup relay (P/B) relay pairs and the close in fault currents are shown in Table 2. The pickup tabs and the CT ratios of the relays are given in Table 3. Table 4 and Table 5 respectively show the coefficients of the (5) and (6).

The transient variations in the system topology have not been considered and a CTI of 0.2 is accepted. The PTDS values after getting from the simulation results and the TDS values after calculations from Eq. (5) have been depicted in Table 6.

Table 6 shows the optimized values of PTDS and TDS respectively obtained from the Gray Wolf optimization simulation and from the values obtained from the proposed

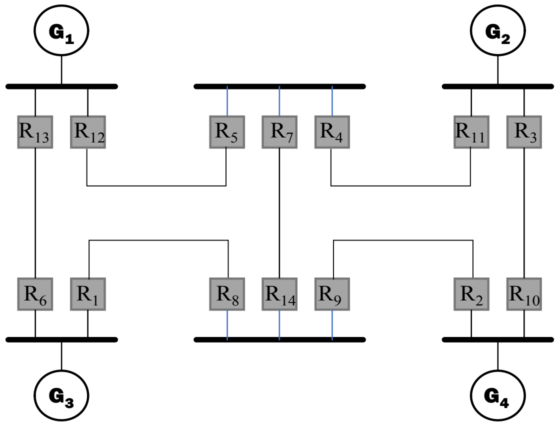

Fig. 4. IEEE 6-Bus system

Table 2. P/B and the close in fault currents

Primary Relay		Backup Relay	
Relay No.	Fault Current (kA)	Relay No.	Fault Current (kA)
1	18.172	13	0.601
2	4.803	3	1.365
3	30.547	4	0.5528
4	5.186	12	3.422
4	5.186	14	1.764
5	2.838	11	1.074
5	2.838	14	1.764
6	18.338	8	0.767
7	4.496	11	1.074
7	4.496	12	3.422
8	2.351	2	0.869
8	2.351	7	1.483
9	6.072	1	4.589
9	6.072	7	1.483
10	4.077	9	0.639
11	30.939	10	0.9455
12	17.705	6	0.861
13	17.821	5	0.977
14	5.457	1	4.589
14	5.457	2	0.868

Table 3. CT Ratios and Pickup Tabs

Relay No.	CT Ratio	Pick-up Tab
1	1200/5	0.8
2	800/5	0.8
3	800/5	1.0
4	800/5	0.5
5	800/5	0.5
6	1200/5	0.5
7	800/5	1.0
8	800/5	0.8
9	800/5	0.5
10	600/5	1.0
11	800/5	1.0
12	800/5	1.5
13	1200/5	0.5
14	800/5	1.0

Table 4. Coefficients of Eq. (5)

a_0	a_1	a_2	a_3
1.86e-2	5.607e-2	3.0128e-3	1.234e-8

Table 5. Coefficients of Eq. (6)

b_0	b_1	b_2	b_3	b_4
0.92964	6.79213	14.03259	-8.43032	2.6798

Table 6. PTDS and TDS values of 6-bus system

Relay No.	PTDS	TDS	Relay No.	PTDS	TDS
1	0.0480	0.5103	8	0.0280	0.1661
2	0.0249	0.1117	9	0.0453	0.4645
3	0.0265	0.1398	10	0.0276	0.1591
4	0.0409	0.3895	11	0.0227	0.0728
5	0.0310	0.2186	12	0.0297	0.1959
6	0.0343	0.2759	13	0.0288	0.1801
7	0.0252	0.1170	14	0.0422	0.4117

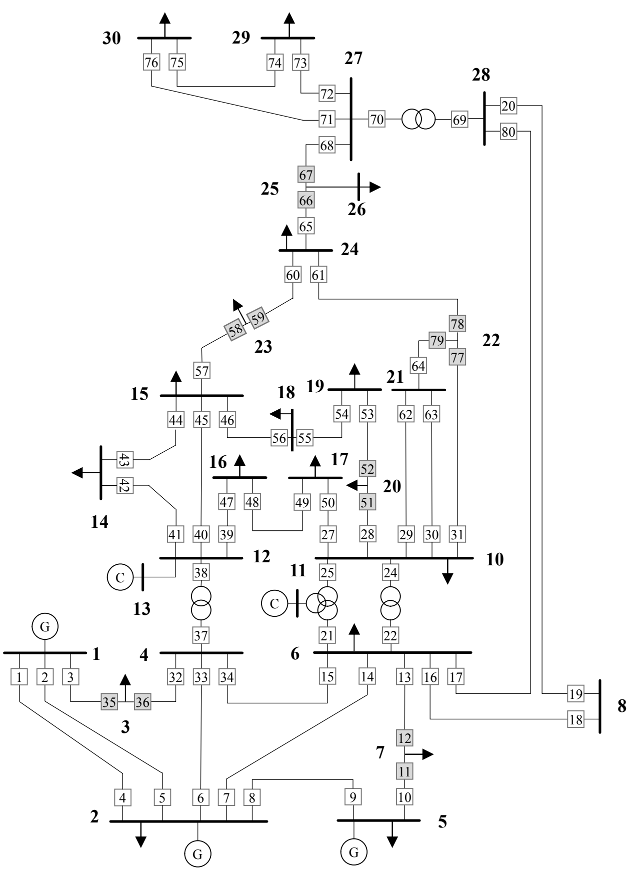

Fig. 5. IEEE 30-bus system

algorithm the time dial setting has been minimized to the optimal value.

5.2 IEEE 30-bus system

The second case study used in our proposed methodology is the IEEE 30-bus system which consists of 76 overcurrent relays as shown Fig. 5 [31]. The optimized

Table 7. Comparison for TDS using proposed GWO, MPSO, GA, TLBO, PSO-DE, PSO and MPSO (NLP) in 6-bus system

Relay No.	GWO	MPSO [17]	GA [26]	TLBO [27]	PSO-DE [28]	PSO [29]	MPSO (NLP) [30]
1	0.5103	1.1794	0.55647	0.3780	0.4064	0.2602	0.5
2	0.1117	0.5	0.5	0.3443	0.7506	0.4739	0.5
3	0.1398	0.5562	0.5	0.2553	0.3872	0.2406	0.5
4	0.3895	0.5	0.50004	0.3346	0.4031	0.2711	0.5
5	0.2186	0.5	0.50002	0.1005	0.2005	0.1268	0.5
6	0.2759	0.5	0.5	0.2376	0.2011	0.1264	0.5
7	0.1170	0.5	0.51584	0.3	0.2003	0.1265	0.5
8	0.1661	0.5	0.5	0.4720	0.2133	0.1265	0.5
9	0.4645	0.5002	0.50003	0.0414	0.2006	0.1268	0.5
10	0.1591	0.5	0.5	0.3323	0.2265	0.1424	0.5
11	0.0728	0.5	0.5	0.2518	0.2610	0.1647	0.5
12	0.1959	0.5	0.59127	0.2704	0.2039	0.1401	0.5
13	0.1801	0.5	0.5	0.1735	0.2002	0.1265	0.5
14	0.4117	0.5	0.52268	0.2817	0.2837	0.1779	0.5

Table 8. Results and comparison of TDS in 30-bus system

Relay No.	GWO	ILP [29]	Relay No.	GWO	ILP [31]
1	0.1452	0.1461	39	0.1655	0.4441
2	0.1180	0.2047	40	0.1306	0.4238
3	0.1236	0.1942	41	0.1491	0.2341
4	0.1143	0.0749	42	0.1741	0.3877
5	0.1672	0.2601	43	0.1208	0.4822
6	0.1468	0.1757	44	0.1182	0.1845
7	0.1334	0.1286	45	0.1243	0.4077
8	0.1469	0.1635	46	0.1572	0.2779
9	0.1332	0.1293	47	0.1429	0.5253
10	0.1468	0.0878	48	0.1117	0.1169
11	0.1202	0.2253	49	0.1056	0.4771
12	0.1368	0.1901	50	0.1499	0.3357
13	0.1528	0.2314	51	0.1649	0.4263
14	0.1483	0.2660	52	0.1504	0.1840
15	0.1536	0.2400	53	0.1038	0.5338
16	0.1270	0.1141	54	0.1203	0.3547
17	0.1352	0.1327	55	0.1107	0.5456
18	0.1286	0.0972	56	0.1539	0.3848
19	0.1065	0.3081	57	0.1031	0.4440
20	0.1075	0.3534	58	0.1590	0.4583
21	0.1162	0.3144	59	0.1095	0.2427
22	0.1408	0.1405	60	0.1168	0.4326
23	0.1260	0.2695	61	0.1051	0.0500
24	0.1449	0.1787	62	0.1097	0.0500
25	0.01058	0.0500	63	0.1592	0.1650
26	0.1546	0.0500	64	0.1274	0.4994
27	0.1288	0.2861	65	0.1114	0.2562
28	0.1136	0.1156	66	0.1399	0.0606
29	0.1613	0.4689	67	0.1153	0.1732
30	0.1076	0.2156	68	0.1106	0.0500
31	0.1232	0.4446	69	0.1555	0.1676
32	0.1307	0.2236	70	0.1421	0.0500
33	0.1500	0.3159	71	0.1301	0.0941
34	0.1096	0.1841	72	0.1369	0.0902
35	0.1108	0.4853	73	0.1033	0.2505
36	0.1169	0.4008	74	0.1245	0.1886
37	0.13399	0.5524	75	0.1438	0.4068
38	0.1125	0.3433	76	0.1121	0.1428

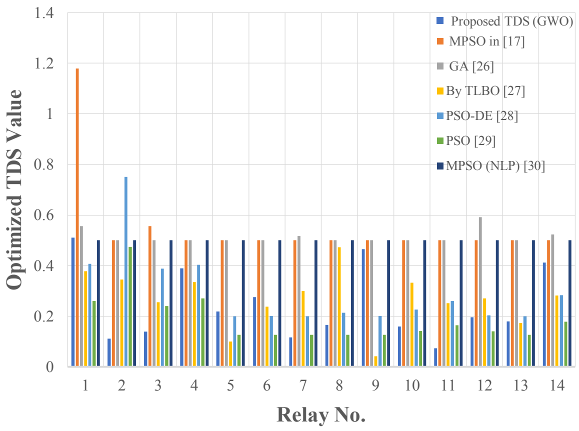

Fig. 6. Graphical representation of the TDS for 6-bus system with literatures

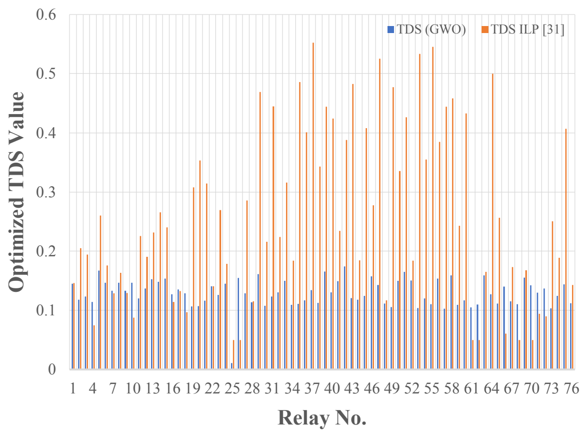

Fig. 7. Graphical representation of the TDS for 30-bus system with literature

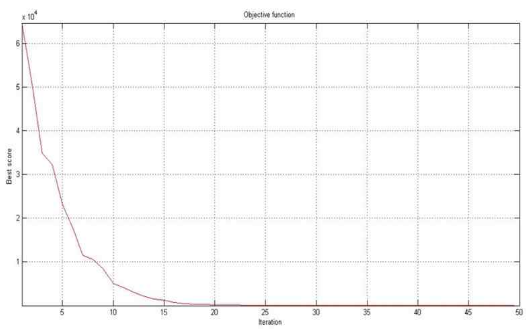

Fig. 8. Convergence graph of GWO

Table 9. Of comparison for case study IEEE 6-bus system

Algorithm	OF (sec)
TLBO [27]	23.7878
MPSO (NLP) [31]	17.0880
PSO-DE [28]	9.2671
PSO [29]	8.1245
MPSO [17]	2.1708
GWO	2.0998

TDS values are shown in Table 8 and the result has been compared with the literature.

On comparing with literature, the results are optimized to the minimum as shown in Table 7 and Table 8.

Fig. 6 and Fig. 7 shows the graphical representation of the optimized TDS values and the results had been compared with the literature.

Fig. 8 shows best values of objective function found during the course of simulations or the convergence characteristics and depicts the convergence of GWO to the optimal solution for meta-heuristic method. It demonstrates that GWO nearly reaches global optimum after 25 iterations. It can be seen that GWO results show better fitness function values over other techniques in literature [32].

From Table 9, OF represents the objective function, though GWO algorithms provide better results and provides the minimum objective function when compared with the other optimization algorithms. This proves the validity of the proposed algorithm in relays coordination.

6. Conclusion

This work presents the optimal coordination of DOCR using a new meta-heuristic technique namely gray wolf optimization technique (GWO). In this work the main aim to be fulfilled was to optimize the time dial settings of directional over current relays. The effectiveness of the proposed algorithm has been implemented on IEEE 6-bus and IEEE 30-bus system. Simulation results show that the GWO algorithm provides effective and robust high-quality solution. Less execution time and better rate of convergence has been achieved in the proposed methodology. Instead of the other optimization techniques in literature survey population size of about 20 to 30 agents had been used as compared to 10 agents in this work that is itself a great achievement.

Acknowledgments

This research was supported by Korea Electric Power Corporation, grant number(R17XA05-38).

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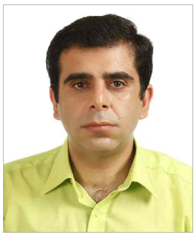
Chang-Hwan Kim He received his B.S. and M.S. degrees from Yeungnam University, Gyeongbuk, Korea in 2013 and 2015, respectively. At present, he is working toward a Ph.D. degree in the dept. of electrical engineering at Yeungnam University. His research interests include power system control and operation, optimal power flow and evolutionary computation, and EMTP and ATP application.

Tahir Khurshaid He received B.E. degree in Electrical Engineering from Jammu University, India in 2011 and master in power system engineering from Galgotias University, Greater Noida, India in 2014. Presently pursuing Ph.D. degree from dept. of electrical engineering, Yeungnam University, South Korea. His areas of interest are power system protection, power system analysis and design and power system deregulation.

Abdul Wadood He received BS degree in Electronic Engineering from University of engineering and technology Peshawar, Pakistan in 2012 and master in electrical engineering from Sarhad University of science and information technology, Peshawar Pakistan in 2015. Presently pursuing Ph.D. degree from Dept. of electrical engineering, Yeungnam University, South Korea. His areas of interest are power system Relaying and power system protection and evolutionary algorithm.



Saeid Gholami Farkoush He received the B.S. degree in electrical engineering from Azad University, Ardebil, Iran, in 2005, and the M.S. from the Department of Electrical Engineering, Islamic Azad University, Science and Research Branch, Tehran, Iran in 2008, and the Ph.D. degree from in the dept. of electrical engineering at Yeungnam University, Gyeongbuk, Korea, in 2017. He is currently a Postdoctoral Research Fellow in the dept. of electrical engineering at Yeungnam University. His current research interests include power factor correction system for EV chargers in the smart grid by using FACTS devices.

Sang-Bong Rhee He received his B.S., M.S., and Ph.D. degrees from Hanyang University, Korea, in 1994, 1999, and 2004, respectively. He was a research professor in the School of Electrical and Computer Engineering, Sungkyunkwan University, Korea. Currently, he is an assistant professor with the dept. of electrical engineering at Yeungnam University, Gyeongbuk, Korea. His research interests include a distribution system control and operation, and artificial intelligence applications to power system protection.