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ORIGINAL ARTICLE

Development and application of an efficient optimizer for optimal coordination of directional overcurrent relays

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Abstract

This paper proposes an enhanced version of grey wolf optimizer (EGWO) to solve the coordination problem of directional overcurrent relays (DOCRs). The EGWO is proposed to improve the convergence characteristics and computation time of the conventional grey wolf optimizer (GWO) by selecting a suitable balance between exploration and exploitation phases. This balance is achieved by exponential decreasing of the control parameter during the iterative process. The EGWO is explored in all search space during predetermined iterations, and then it fast converges to the best optimal solution by local exploitation around the optimal solutions. The proposed optimization technique is applied to solve the coordination problem of DOCRs. The main objective of optimal coordination of DOCRs is to minimize total operating time of all primary relays with sustaining the selectivity between relay pairs. The feasibility and performance of the proposed technique for solving the coordination problem of DOCRs are investigated using four different systems, compared with several well-known techniques. The obtained results prove the effectiveness and superiority of the proposed technique compared with these techniques. The proposed technique is able to find the optimal relay settings and minimize the total operating time of relays (with a reduction ratio about 19.3995% relative to the conventional GWO) without any miscoordination. In addition, DIgSILENT PowerFactory is used to validate the proposed technique.

Keywords Directional overcurrent relays · Optimal coordination · Coordination time interval · Enhanced grey wolf optimizer

1 Introduction

The complexity of power system operation is increasing as the size of the power system is increasing rapidly. Protection relays play an important role in keeping the reliability of power system at a high level [1]. The main objective of a protective relay is to identify and isolate the faulted elements and keep the non-faulted elements in service or, at least, minimize damage in the system due to abnormal conditions [2]. DOCRs are generally applied in the protection of sub-transmission and distribution systems [3]. DOCRs calculate the direction of a fault by comparing the phase angles of currents, or the phase angle of a current with that of voltage to determine the direction of a fault [4]. DOCRs operate when the current magnitude exceeds a reference current (pickup current) and flows in front of relay [5]. If the fault is located behind the relay, then no action will be taken [6]. The operating time of DOCRs is based on pickup current (Ip) or plug setting (PS) and time

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dial setting (TDS). The right selection of these settings plays an important role in the optimal coordination of DOCRs [7]. The reliable coordination of DOCRs means that the primary relay should isolate the fault in its own zone quickly to limit the system outage to the smallest area. The backup relay should be operated after a specified time delay to clear the fault in case primary relay failed to operate [8]. Hence, the main objective of optimal coordination of DOCRs is to find suitable relay settings which minimizes the operating time of DOCRs. Different techniques have been proposed to solve the coordination problem of DOCRs. Firstly, the calculation of relay settings was done manually. This calculation was very time-consuming and inappropriate practically [9]. Then, the trial-and-error technique was initiated to find the optimal relay setting using computers [10]. This technique has a slow rate of convergence, and the obtained TDS values of relays using this approach are relatively high which increases the stress on electrical equipment and leads to reduce their life or even damage [8]. In the late 1980s, linear programming (LP) techniques, including two-phase simplex methods [11], simplex [12], Big-M methods [13], dual simplex [12], have been used to solve the coordination problem of DOCRs [14]. In this technique, the operating time of DOCRs is optimized by TDS in which Ip is assumed to be predetermined [15]. In contrast, LP is a fast and simple technique, which only helps in optimizing the TDS and does not yield an optimal solution [15]. Nonlinear programming (NLP) like sequential quadratic programming (SQP) [12] has been used to find the optimal coordination of DOCRs. In this technique, all the relay settings are optimized simultaneously [9]. However, NLP gives better results, is very complex and maybe gets stuck in local minima due to its dependency on the initial values of Ip and TDS [9, 10].

Recently, solving the coordination problem of DOCRs using artificial intelligence (AI) has received considerable attention [7]. Many techniques based on population have been proposed to deal with this problem such as firefly technique (FFA) [8], group search optimization (GSO) [16], cuckoo search technique (CSA), harmony search (HS) [9] and gravitational search-based technique (GS) [17], backtracking search technique (BSA) and enhanced BSA [18, 19] and electromagnetic field optimization (EFO) and modified electromagnetic field optimization (MEFO) [20]. The comprehensive study between different population-based techniques such as genetic technique (GA), particle swarm optimization (PSO) and differential evaluation (DE) for solving DOCRs coordination problem has been presented in [21]. Hybrid techniques, which utilize the features of nature-inspired and classical techniques, have been successfully proposed to solve the coordination problem of DOCRs such as cuckoo search technique (CSA)-FFA [22], GA-NLP [23], BBO-differential evaluation (DE) [24] and biogeography-based optimization (BBO)-LP [10], gravitational search technique (GSA)-SQP [25], evaporation rate water cycle technique [26] and modified water cycle technique (MWCA) [27].

The GWO technique is a recent population-based technique developed by Seyedali et al. [28]. The GWO begins with an initial population of candidate solution called search agents. The design variables are represented as the search agent. Each search agent is assessed according to the main objective function, and then it is classified as follows: the best candidate solution is alpha, the second candidate solution is beta, the third candidate solution is gamma and the rest of candidate solutions are omega. This cycle is repeated until convergence criteria are met.

In this paper, the EGWO technique is proposed and applied to determine the optimal coordination and minimize the operating time of DOCRs. However, the topic discussed and contribution of the work could be summarized as:

- An effective optimization technique called enhanced grey wolf optimizer technique (EGWO) is proposed and applied for solving the optimal coordination problem of DOCRs;
- EGWO technique is proposed to improve the performance of conventional GWO;
- In the proposed technique, the conventional GWO technique performance is improved by selecting a suitable balance between exploration and exploitation phases. This is achieved by exponentially decreasing the control parameter during the iterative process;
- The performance of the proposed technique is assessed using different standard test systems (eight-bus, nine-bus, 15-bus and 30-bus);
- Using the proposed technique, remarkable minimization in total operating time of all primary relays subject to the sequential operation between relay pairs is achieved;
- The proposed technique is compared with other well-known optimization techniques;

- The results obtained by the proposed technique are validated using benchmark DIgSILENT PowerFactory;
- The obtained results prove the effectiveness and superiority of the proposed EGWO to solve the DOCRs coordination problem, compared with conventional GWO and other optimization techniques;
- The proposed optimization technique can be used to effectively solve other optimization problems.

Remainder of this paper is organized as follows. Section 2 explains the problem formulation of DOCRs coordination. Section 3 illustrates the conventional GWO and proposed EGWO. Section 4 presents the main results of three different test systems obtained by the proposed EGWO, conventional GWO and other well-known optimization techniques. In addition, results validation using DIgSILENT PowerFactory is presented in the same section. Finally, the main conclusions and suggestions are provided in Sect. 5.

2 Problem statement

The main purpose of solving the coordination problem of DOCRs is to maintain the security and reliability of electric power system. This purpose can be achieved by finding the optimal relay settings which minimize the summation of operating times for all primary relays and at the same time keep the validation of the sequential operation between primary and backup relays [29]. The coordination problem of DOCRs can be stated as a constraint optimization problem, and the objective function (*OF*) of this problem can be written as follows:

$$\text{Minimize}(\text{OF}) = \sum_{i=1}^{n} Wi \cdot T_{i,n} \tag{1}$$

where $T_{i,n}$ is the operating time of primary relay, n is the number of relays; and W_i is the weight which represents fault probability in a line and is usually set to be equal to one [8].

The operating time of each protective relay can be expressed as follows:

$$T_{i,n} = \frac{\alpha \times \text{TDS}^i}{\left(\frac{I_f^i}{I_p^i}\right)^{\beta} - \gamma} \tag{2}$$

$$I_p^i = \text{CT}^i \times \text{PS}^i \tag{3}$$

where γ, β and α are constant values representing the characteristics of relay, I_f is the fault current (A), CT is the current transformer ratio for relay i, TDS is the time dial setting for relay i and Ip is the pickup current for relay i [20, 30]. In this paper, the inverse definite minimum time (IDMT) characteristic is used for fair comparison with the performance of other optimization techniques, where the constants γ, β and α are given as 1.0, 0.02 and 0.14, respectively, according to standard IEC 60225-3 [31]. The objective function in (1) should be achieved under two categories of constraints: relay characteristics constraints and coordination constraints.

2.1 Relay characteristics constraints

The limits of relay settings can be described as follows:

$$I\text{p}_{\min}^i \le I\text{p} \le I\text{p}_{\max}^i \tag{4}$$

$$\text{PS}_{\min}^i \le \text{PS}^i \le \text{PS}_{\max}^i \tag{5}$$

$$\text{TDS}_{\min}^i \le \text{TDS}^i \le \text{TDS}_{\max}^i \tag{6}$$

where $I\text{p}_{\max}$ and $I\text{p}_{\min}$ are the upper and lower pickup currents, respectively, and $\text{PS}_{\max}$ and $\text{PS}_{\min}$ are the upper and lower of PS, respectively. The range of Ip and PS depends on the minimum fault current and the maximum load current to ensure that the relay is sensitive to the smallest fault current, and it will not mal-operate under normal load [23, 32]. $\text{TDS}_{\max}$ and $\text{TDS}_{\min}$ are the range settings of TDS, respectively, where the limits of TDS depend on the relay manufacturer [33].

2.2 Coordination constraint

Both primary and backup relays sense the fault simultaneously [23]. To ensure relays coordination, a certain time period is required between the operating times of relay pairs [9]. This means the backup relays must be initiated after time period known as the coordination time interval (CTI) in case the primary failed to operate [10]. The CTI depends on circuit breaker operating time, a relay error and safety margin and kind of relays [34]. The CTI can be described as follows:

$$T_{\text{backup}} - T_{\text{primary}} \ge \text{CTI} \tag{7}$$

where T_{primary} and T_{backup} are the operating times of primary and backup relays, respectively. The value of CTI varies from 0.20 to 0.50 s [35].

3 Proposed optimization technique

3.1 Conventional grey wolf optimizer

The GWO technique is inspired from the leadership hierarchy and hunting mechanism of grey wolves in nature [28, 36]. Alpha (α) and beta (β) are the first and second levels in the hierarchy, respectively. The third level in the group is called delta (δ). Omega (ω) is the lowest ranking in the hierarchy and represents the rest of candidate solutions [28].

3.1.1 GWO mathematical modelling

The mathematical models of social hierarchy, encircling and attacking prey can be explained as follows [28]:

Encircling prey: During the hunt, grey wolves encircle prey, which can be mathematically written as:

$$\vec{X}(k+1) = \vec{X}(k) - \vec{A} \cdot \vec{D} \tag{8}$$

$$\vec{D} = \left| \vec{C} \cdot \overrightarrow{X_p}(k) - \vec{X}(k) \right| \tag{9}$$

$\vec{X}$ indicates the position vector of a grey wolf and $\overrightarrow{X_P}$ is the position vector of the prey. $\vec{D}$ is considered as a difference vector, k indicates the current iteration and $\vec{A}$ and $\vec{C}$ are coefficient vectors and are determined as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r_1} - \vec{a} \tag{10}$$

$$\vec{C} = 2 \cdot \vec{r_2} \tag{11}$$

where $\vec{r_1}$ and $\vec{r_2}$ are random numbers between [0, 1] and components of $\vec{a}$ are linearly decreased from 2 to 0.

- Hunting: Alpha, beta and delta have better knowledge about the position of prey. The other search agents and their positions are updated according to the position of three best search agents. The hunting mechanism can be mathematically described as:

$$\overrightarrow{D_\alpha} = \left| \overrightarrow{C_1} \cdot \overrightarrow{X_\alpha} - \vec{X} \right| \tag{12}$$

$$\overrightarrow{D_\beta} = \left| \overrightarrow{C_2} \cdot \overrightarrow{X_\beta} - \vec{X} \right| \tag{13}$$

$$\overrightarrow{D_\delta} = \left| \overrightarrow{C_3} \cdot \overrightarrow{X_\delta} - \vec{X} \right| \tag{14}$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1} \cdot (\overrightarrow{D_\alpha}) \tag{15}$$

$$\overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2} \cdot (\overrightarrow{D_\beta}) \tag{16}$$

$$\overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{A_3} \cdot (\overrightarrow{D_\delta}) \tag{17}$$

$$\vec{X}(k+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3} \tag{18}$$

Attacking prey: The grey wolves converge towards the prey to attack when $|A| < 1$.

Search for prey: The grey wolves diverge from each other to search for a fitter prey when $|A| > 1$.

3.2 Enhanced grey wolf optimizer

The exploration and exploitation are two conflicting phases, and both are important for a robust search cycle. They are fundamental concepts of any search technique. A proper balance between exploration and exploitation is the goal of all meta-heuristic techniques. This balance can guarantee to find the best global minima solution in the search space. The exploration has the ability to search into

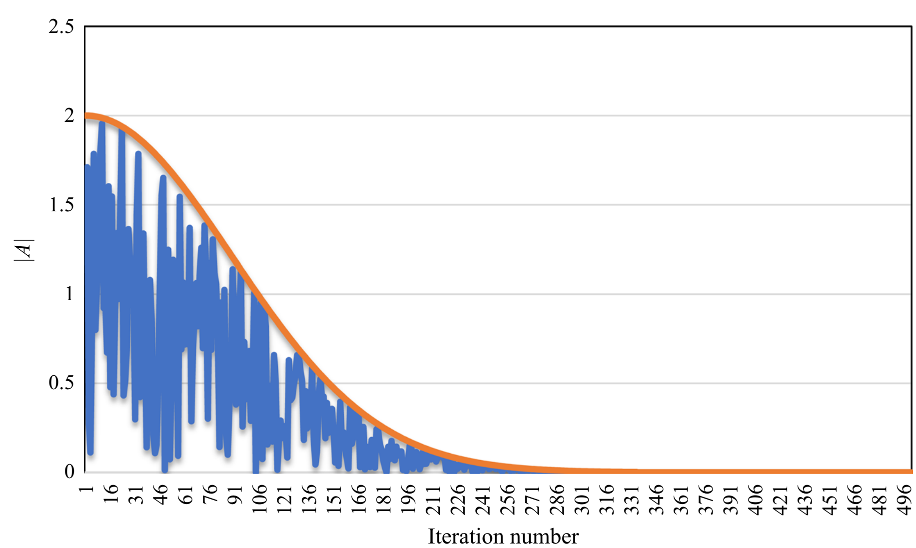

Fig. 1 Variation in parameter $|A|$ over the course of iterations in the proposed EGWO

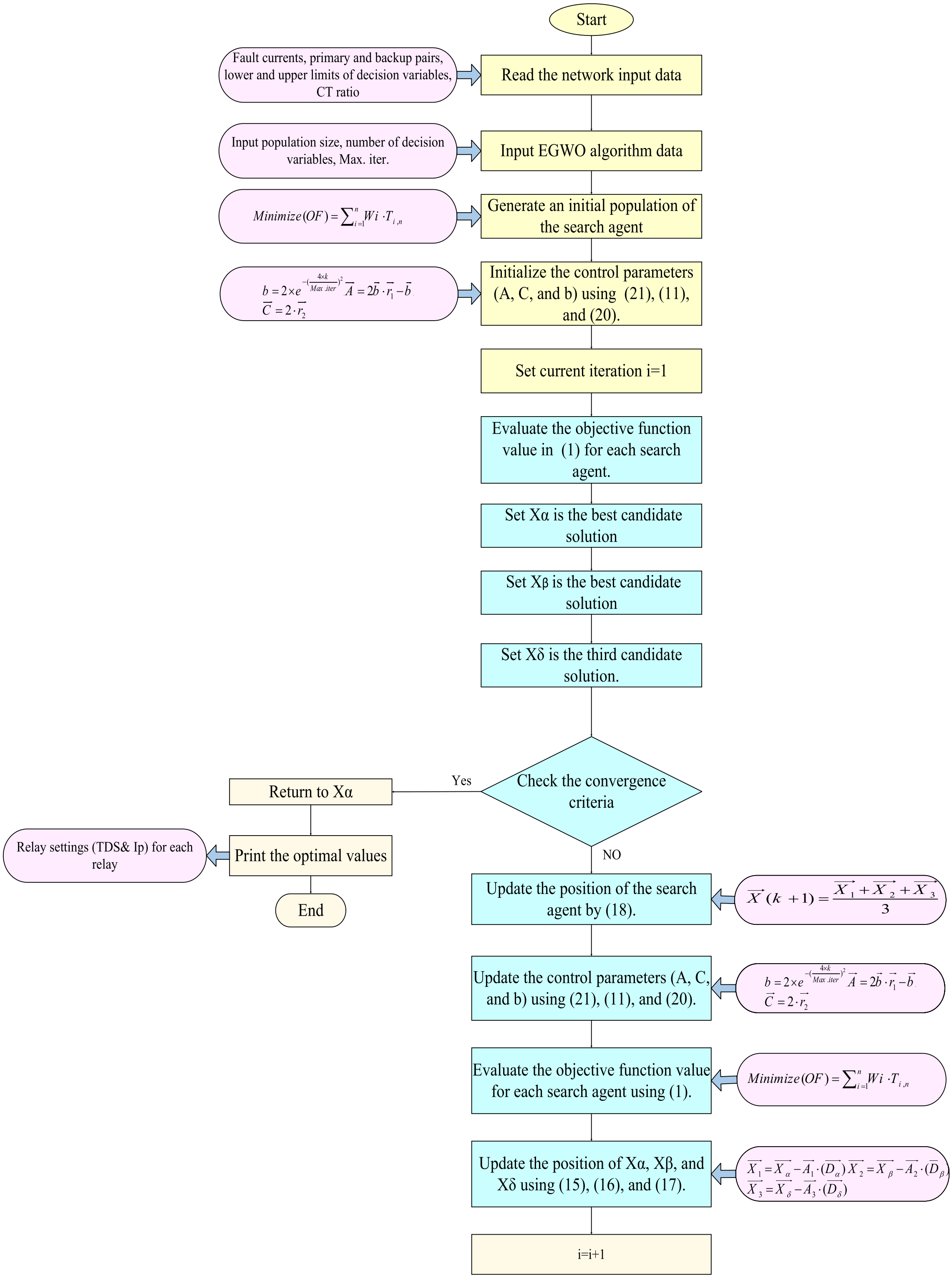

Fig. 2 Solution process of DOCRs coordination problem using the proposed EGWO

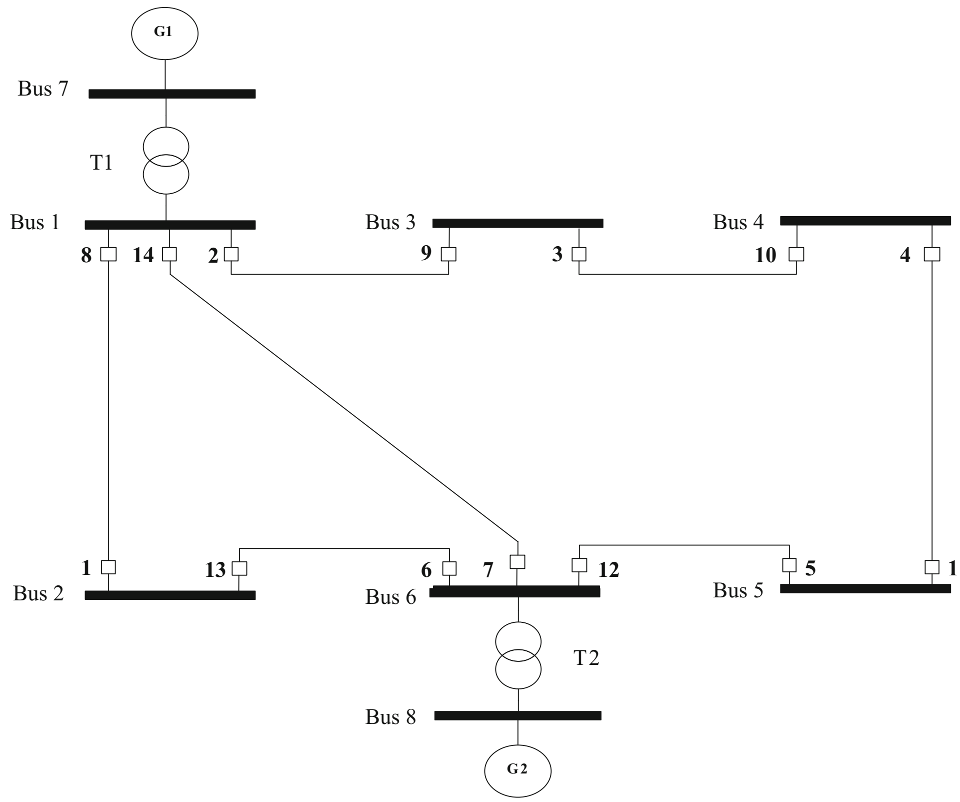

Fig. 3 Single-line diagram of eight-bus test system

Table 1 Optimal relay settings of eight-bus system

Relay no.	EGWO		GWO	
	*I*p (A)	*TDS* (sec)	*I*p (A)	*TDS* (sec)
1	479.8054	0.072371	471.5639	0.079891
2	453.0416	0.244386	426.0431	0.265799
3	256.9887	0.203102	92.59924	0.310685
4	474.7005	0.077288	437.8511	0.084293
5	274.9477	0.05	281.1445	0.050169
6	386.4771	0.166068	193.1957	0.23872
7	272.1896	0.244733	236.1357	0.278032
8	464.5557	0.146353	199.4853	0.340652
9	273.1938	0.05	292.1015	0.050109
10	479.7386	0.079784	291.0165	0.1196
11	477.3866	0.148752	189.5863	0.25509
12	473.0546	0.23663	168.3451	0.400331
13	478.8183	0.072082	174.933	0.23986
14	304.9012	0.226281	188.6815	0.331382
OF (*s*)	6.1671		7.3988	

Table 2 Primary and backup operating times of relays and CTI values of eight-bus system

Relay pairs		$T_{\text{Primary}}(s)$	$T_{\text{backup}}(s)$	CTI(s)
1	6	0.290342	0.590342	0.3000
2	1	0.674647	0.974647	0.3000
3	2	0.674647	0.974647	0.3000
4	3	0.541179	0.841179	0.3000
5	4	0.345635	0.645635	0.3000
6	5	0.218096	0.518096	0.3000
6	5	0.443437	0.908335	0.4649
7	5	0.443437	0.965032	0.5216
7	13	0.606524	0.908335	0.3018
8	7	0.606524	0.965032	0.3585
8	9	0.421967	0.974647	0.5527
9	10	0.421967	0.895667	0.4737
10	11	0.208787	0.508787	0.3000
11	12	0.349427	0.649427	0.3000
12	13	0.51427	0.81427	0.3000
12	14	0.665032	0.965032	0.3000
13	8	0.665032	0.965032	0.3000
14	1	0.302095	0.602095	0.3000
14	9	0.585689	0.974647	0.3890

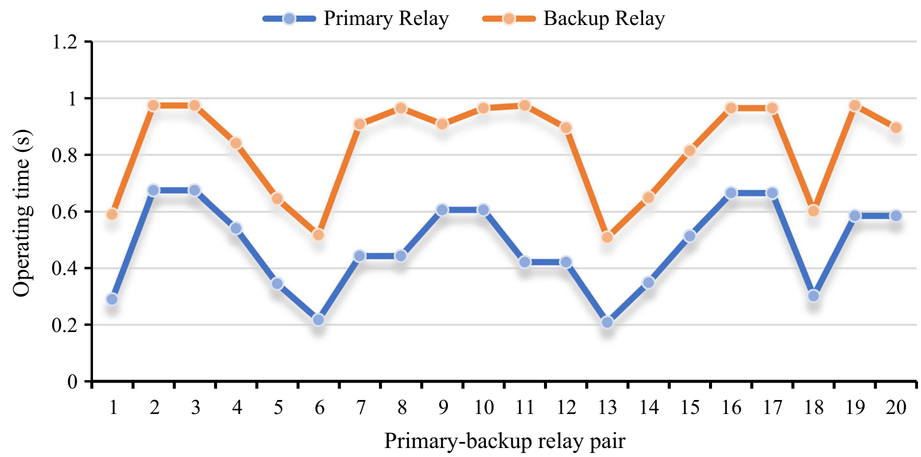

Fig. 4 Operating times of primary–backup relay pair of eight-bus system

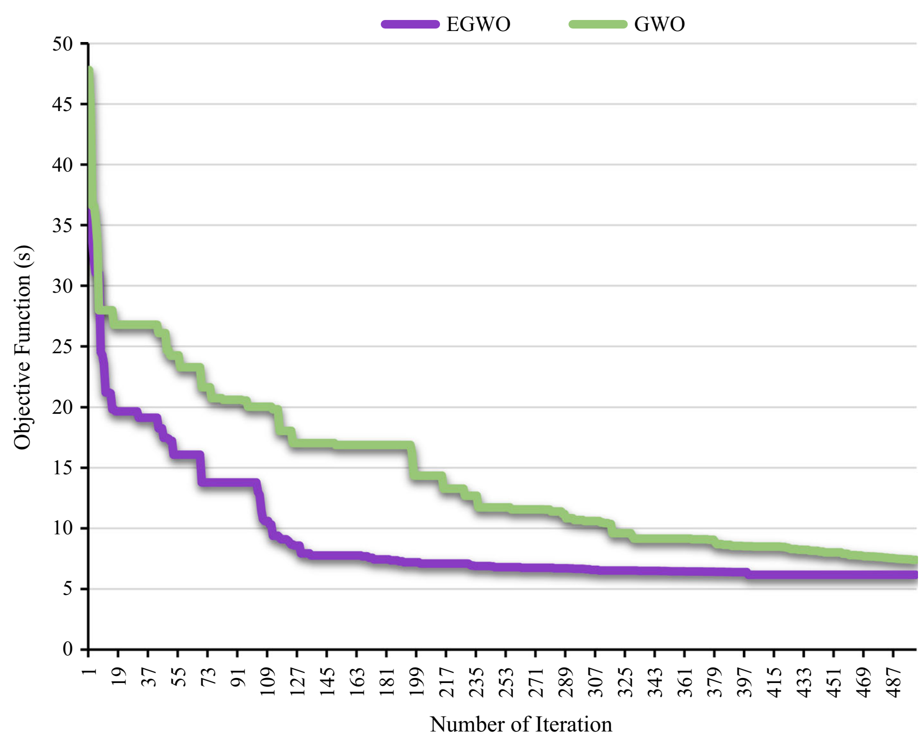

Fig. 5 Convergence characteristics of EGWO and GWO (eight-bus system)

Table 3 Minimum operating time of DOCRs obtained by different optimization techniques (eight-bus system)

Methods	Objective function (s)
EGWO	6.1671
EFO	7.611
MEFO	6.349
DE	6.654
PSO	10.421
HS	11.760
BH	11.401
MWCA	6.337
WCA	7.89

the solutions space, while exploitation aims to search locally around the promising solutions [37].

In conventional GWO technique, the exploration and exploitation are guaranteed by the adaptive values of parameter a [28]. The component of a is linearly decreased from 2 to 0 over the course of iterations [28].

In this paper, the control parameter is suggested to exponentially decrease instead of decreasing linear, which can be expressed as follows:

$$b = 2 \times e^{-\left(\frac{4\times k}{\text{Max.iter}}\right)^2}. \quad (19)$$

The parameter b is suggested to be used in the GWO technique instead of parameter a in order to achieve a suitable balance between the exploitation and exploration

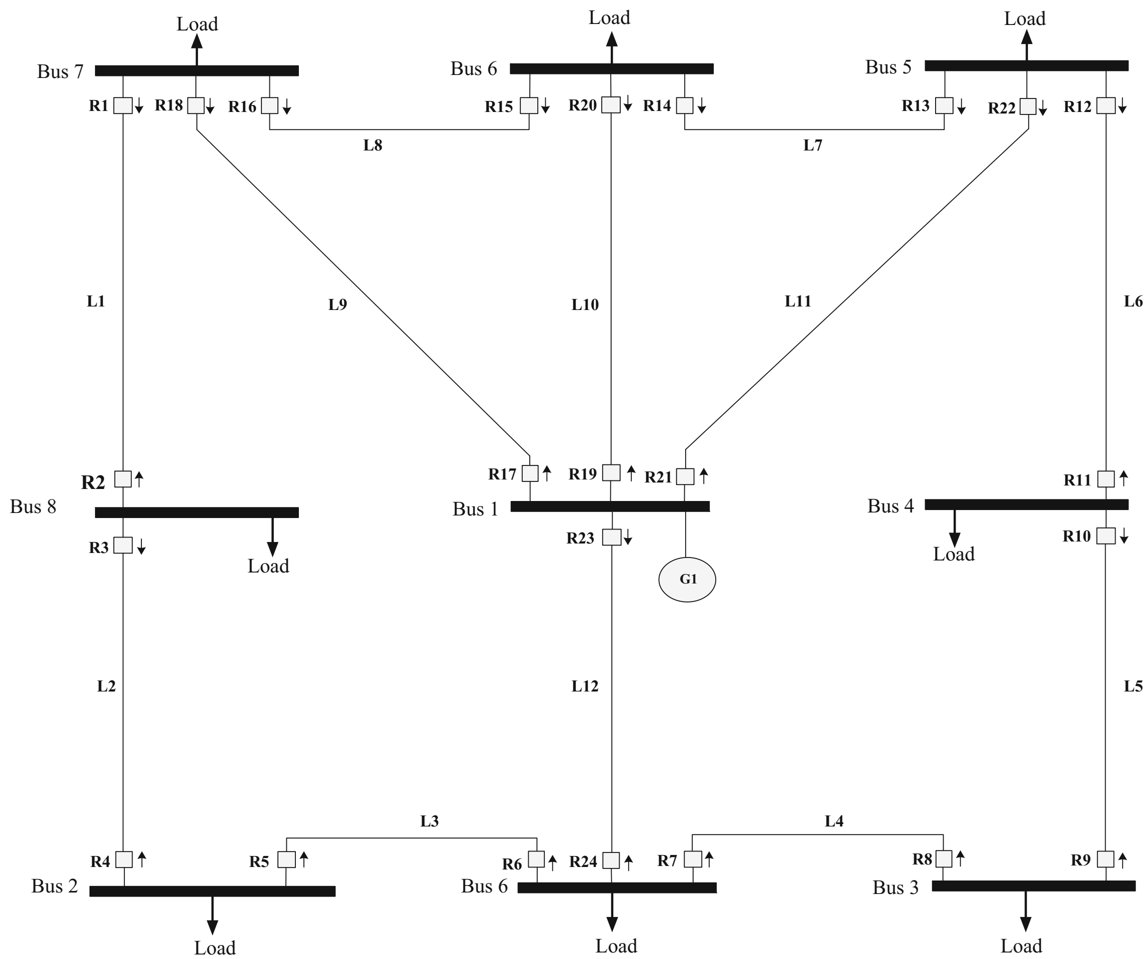

Fig. 6 Single-line diagram of nine-bus test system

phases. This parameter is exponentially decreased during the iterative process in order to accelerate the convergence of GWO technique and reduce the total computation time.

As mentioned before, the parameter $\overrightarrow{A}$ forces the technique to search for the candidate solutions when $|A| > 1$ and converge towards the prey when $|A| < 1$. In the proposed technique, the parameter $\overrightarrow{A}$ can be calculated as follows:

$$\overrightarrow{A} = 2\overrightarrow{b} \cdot \overrightarrow{r_1} - \overrightarrow{b}. \tag{20}$$

Figure 1 shows the exponential change of parameter $\overrightarrow{A}$ during the iterative process.

The proposed EGWO technique is carried out in the following steps:

Step 1 Generate initial population of the position candidate solutions and initialize the iteration counter $k = 1$;

Step 2 Initialize the control parameters (A, C and b);

Step 3 Classify the candidate solution as follows: the best candidate solution is $X\alpha$, the second candidate is $X\beta$ and the third candidate solution is $X\delta$;

Step 4 Initialize the control parameters A, C and b using (11), (19) and (20), respectively;

Step 5 Update the position of current candidate solutions using (18);

Step 6 Update A, C and b;

Table 4 Optimal relay settings of nine-bus system

Relay no.	EGWO		GWO	
	Ip (A)	TDS (s)	*Ip* (A)	TDS (s)
1	791.8844	0.025	783.6374	0.030948
2	350.989	0.02877	332.8451	0.031404
3	666.3032	0.025	420.8579	0.047875
4	567.8623	0.028797	32.45602	0.178905
5	431.237	0.0272	450.963	0.027319
6	723.5917	0.025	768.9157	0.032083
7	709.6026	0.025	508.9695	0.062067
8	449.2443	0.025	454.8254	0.025103
9	604.4345	0.025	41.75431	0.176987
10	647.3784	0.025811	104.5024	0.114115
11	380.6134	0.025	352.2143	0.038204
12	447.5712	0.026059	501.0687	0.028418
13	582.9814	0.025204	173.7443	0.103415
14	601.3346	0.030745	39.4615	0.162875
15	610.4529	0.030044	147.8282	0.098236
16	599.6976	0.025	671.2402	0.027509
17	598.0965	0.02877	553.8279	0.043056
18	551.65	0.025	553.2942	0.025047
19	739.5141	0.028797	710.506	0.036666
20	513.9729	0.027237	542.6102	0.025387
21	640.7599	0.025	589.2271	0.056905
22	551.65	0.025	555.4028	0.025116
23	747.4439	0.025	786.4567	0.032189
24	633.15	0.025	633.6149	0.025
$\sum_{i=1}^{N} T_i(s)$	2.628136		3.869932	

Step 7 Evaluate the objective function value for candidate solutions;

Step 8 Update the candidate solution as follows: the best candidate solution is $X\alpha$, the second candidate is $X\beta$ and the third candidate solution is $X\delta$;

Step 9 Update the iteration counter $k = k+1$

Step 10 Repeat the process from Step 5 to Step 9 till the convergence criteria are met ($k \geq$ maximum number of iterations);

Step 11 Print the optimal solution ($X\alpha$)

However, the overall solution process of proposed EGWO for solving the coordination problem of DOCRs is summarized in Fig. 2.

Table 5 Primary and backup operating times of relays and CTI of 9-bus system

Relay pairs		T_{Primary} (s)	T_{backup} (s)	CTI(s)
1	15	0.094673	0.321901	0.22722
1	17	0.094673	0.294673	0.2
2	4	0.128915	0.328915	0.2
3	1	0.119812	0.321131	0.201319
4	6	0.130139	0.330142	0.200003
5	3	0.132695	0.332695	0.2
6	8	0.09547	0.379195	0.283725
6	23	0.09547	0.295943	0.200472
7	5	0.094427	0.379195	0.284768
7	23	0.094427	0.295943	0.201515
8	10	0.125468	0.325468	0.2
9	7	0.117875	0.318293	0.200418
10	12	0.121237	0.321237	0.2
11	9	0.118348	0.318348	0.2
12	14	0.097454	0.321901	0.224447
12	21	0.097454	0.300465	0.203011
13	11	0.093939	0.321901	0.227962
13	21	0.093939	0.300465	0.206526
14	16	0.108964	0.320811	0.211848
14	19	0.108964	0.324671	0.215707
15	13	0.107329	0.307329	0.2
15	19	0.107329	0.324671	0.217343
16	2	0.094655	0.321901	0.227246
16	17	0.094655	0.294673	0.200018
17	–	0.087817	–	–
18	2	0.121901	0.321901	0.2
18	15	0.121901	0.321901	0.2
19	–	0.074084	–	–
20	13	0.105598	0.307329	0.201731
20	16	0.105598	0.320811	0.215214
221	–	0.083818	–	–
22	11	0.121901	0.321901	0.2
22	14	0.121901	0.321901	0.2
23	–	0.072422	–	–
24	5	0.179195	0.379195	0.2
24	8	0.179195	0.379195	0.2

4 Results and discussions

The proposed technique has been tested using four test systems and compared with the conventional GWO and other well-known optimization techniques (GA [21],

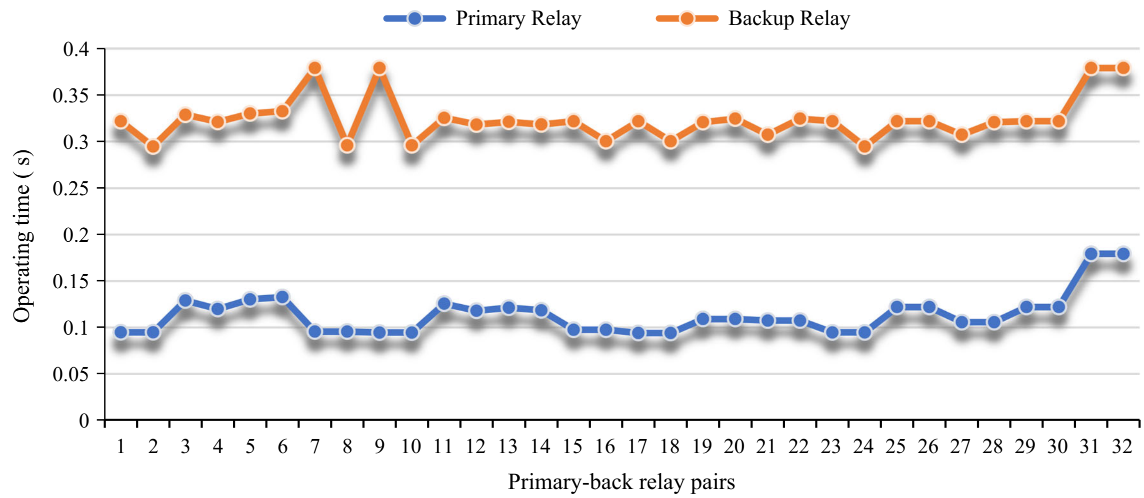

Fig. 7 Operating time of primary–backup relay pairs for nine-bus system

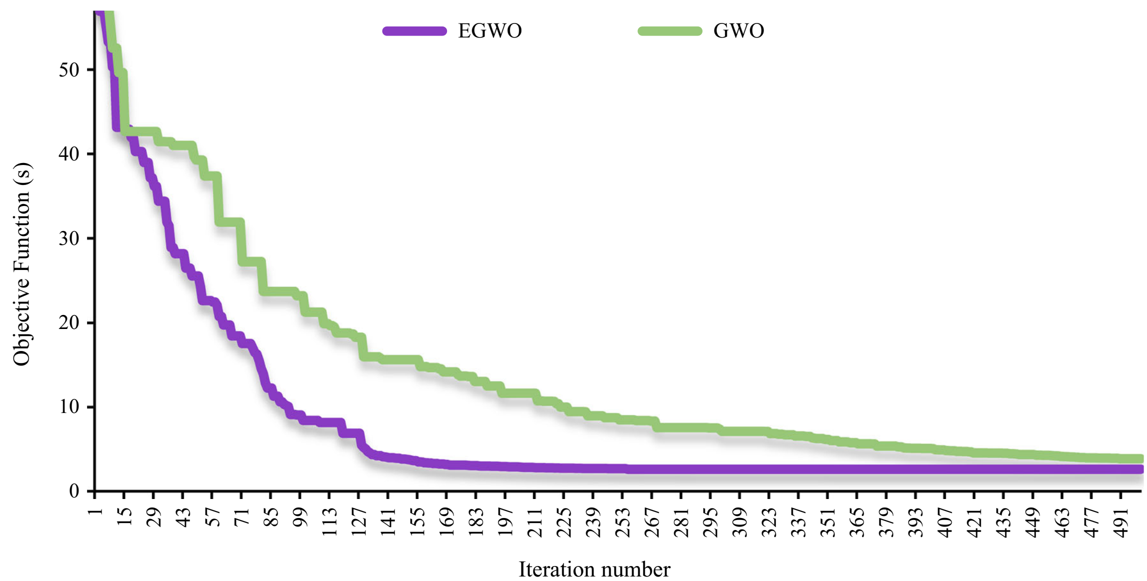

Fig. 8 Convergence characteristics of EGWO and GWO (nine-bus test system)

MEFO [20], HS [9], GA-NLP [23], GS[17], PSO [21], GSA-SQP [25], BBO-LP [10], DE [21], CSA [34], BSA [18], EBSA [19], GSO [16], FFA [38], MWCA[26], EWCA[27]). The stopping criterion for each test case has been chosen as 500 iterations. The proposed technique has been carried out in MATLAB environment using a 2.3 GHz PC with 4 GB RAM under Windows 7 operating systems.

4.1 Case 1: eight-bus test case

The proposed EGWO is validated on the eight-bus system. This system consists of two generators, two transformers, seven lines and 14 relays, as shown in Fig. 3. The TDS_{min} and TDS_{max} limits are 0.05 and 1.1, respectively. The CTI is set to 0.3 s [19]. The details of this system such as the

Table 6 Minimum operating time of DOCRs obtained by different optimization techniques (nine-bus system)

Methods	Objective function (*s*)
EGWO	2.6281
GA	14.5426
PSO	13.9472
MEFO	5.2250
HS	4.9046
EFO	6.0500
GA-NLP	6.1786
GSA	14.7384
GSA-SQP	8.8923
SQA	10.2030
BBO-LP	4.8000
DE	8.6822
FFA	4.832
MWCA	3.628
WCA	5.740

primary and backup relationship of relay pairs, fault currents and *Ip* ranges are given in [22].

The optimal values of Ip and TDS using EGWO and GWO are tabulated in Table 1. From this table, it can be noticed that the optimal solution obtained by EGWO is better than the solution obtained by GWO technique. The operating time of primary and backup relays and CTI value using EGWO are listed in Table 2 and represented graphically in Fig. 4. From Table 2 and Fig. 4, it can be observed that the primary relays operate first and after coordination time margin the backup relays operate in case primary relays failed to isolate the fault. From Tables 1 and 2, it can be observed that the proposed technique satisfies all the constraints of relay setting and coordination constraints associated with primary/backup relay pairs.

The convergence characteristics of EGWO and GWO techniques are shown in Fig. 5. From this figure, it can be observed that the EGWO technique is able to find the best optimal solution and gives better convergence compared with GWO technique. In addition, it can be noticed that the operating time of all primary relays obtained by EGWO is reduced to 16.64% which is less than that obtained by the conventional GWO. The required computational time of EGWO is 32.4 s after 400 iterations, while it is 42.07 s for GWO after 495 iterations.

The minimum operating time of DOCRs obtained by the EGWO and other well-known optimization techniques is given in Table 3. From this table, it can be observed that the proposed EGWO gives the least objective function which confirms its robustness for solving the coordination problem of DOCRs.

4.2 Case 2: nine-bus test system

In this case, the proposed technique is validated using the nine-bus test network [23]. Figure 6 shows the single-line diagram of this system. In this system, there are 12 lines (L1, L2, … , L12), 24 relays (R1, R2, … , R24) and 32 primary and backup relay pairs.

To coordinate the settings of all the 24 relays, there are 48 decision variables, i.e. TDS_1 to TDS_{24} and Ip_1 to Ip_{24}. All buses of the network and DOCRs in Fig. 6 are numbered according to [23]. The initial ranges for $\mathrm{TDS}_{\min}$ and $\mathrm{TDS}_{\max}$ are 0.025 and 1.2, respectively. The $I\mathrm{p}_{\min}$ and $I\mathrm{p}_{\max}$ limits are given in [20]. The CT ratio for each relay is 500:1, and the CTI is set to 0.2 s as in [20]. Further details of this system such as primary and the backup relationship between relay pairs and fault currents are given in [23].

The optimal values of relay settings using EGWO and GWO are tabulated in Table 4. From this table, it can be noticed that the optimal solution obtained by EGWO is better than that obtained by GWO technique. The operating time of primary and backup relays and CTI value using EGWO are listed in Table 5 and represented graphically in Fig. 7. From Table 5 and Fig. 7, it can be observed that the primary relays operate first and after coordination time margin the backup relays operate in case primary relays failed to isolate the fault.

From Tables 4 and 5, it can be observed that the proposed technique satisfies all the constraints of relay setting and coordination constraint associated with primary/backup relay pairs.

The convergence characteristics of EGWO and GWO techniques are shown in Fig. 8. From this figure, it can be observed that the EGWO technique succeeded in finding the global optimal solution and giving better convergence compared with GWO technique. In addition, it can be noticed that the operating time of all primary relays obtained by the EGWO is reduced to 32.088% less than that obtained by the conventional GWO. The required computational time for EGWO is 35 s after 250 iterations, while it is 68.8 s for GWO after 485 iterations.

The minimum operating time of DOCRs obtained by the proposed technique and other well-known optimization techniques is given in Table 6. From this table, it can be

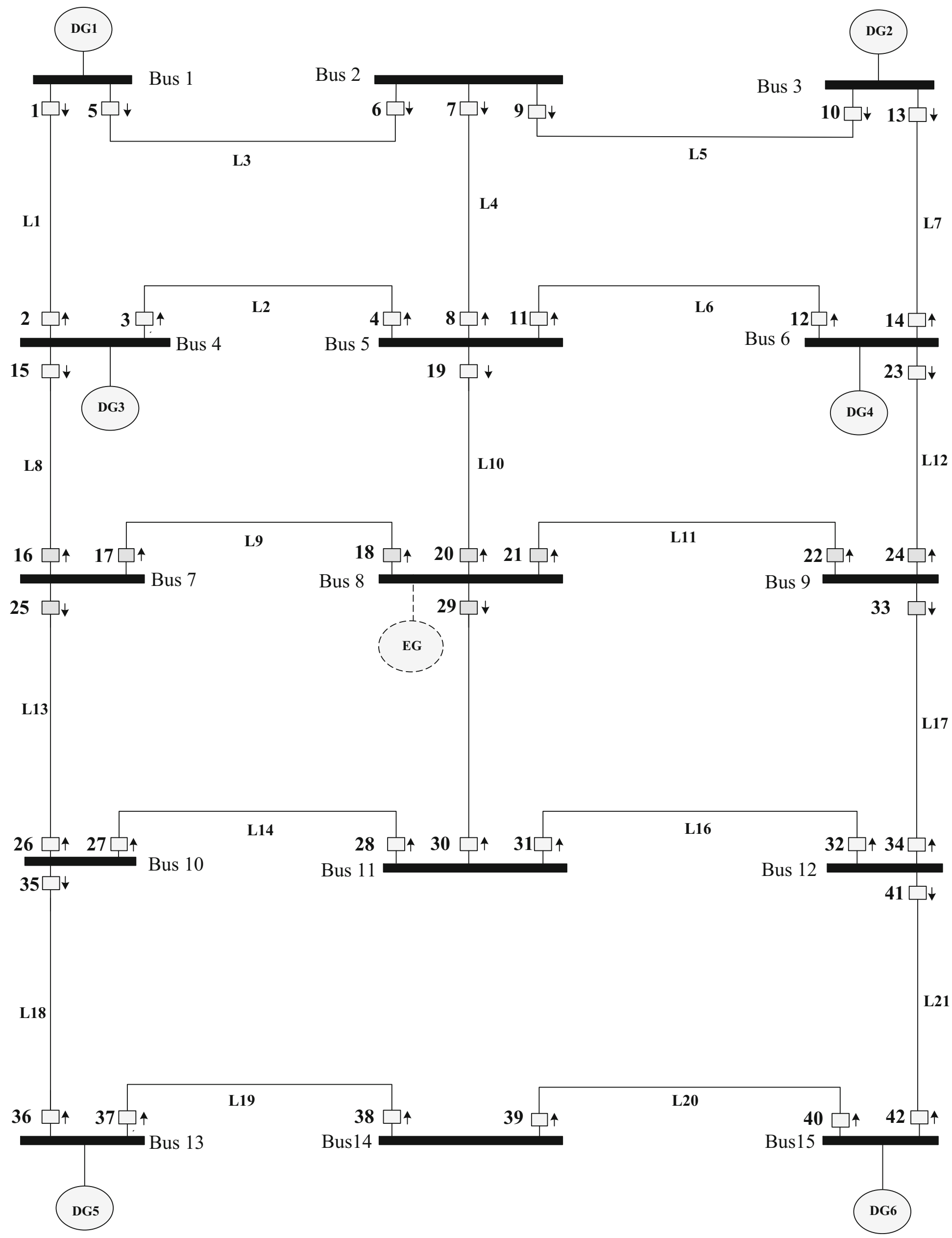

Fig. 9 Single-line diagram of 15-bus test system

observed that the proposed technique gives the least objective function which confirms its robustness for solving the coordination problem of DOCRs.

4.3 Case 3: 15-bus test system

The third test system considered in this section is 15-bus system [29]. The single-line diagram of this system is shown in Fig. 9. In this system, there are 21 lines (L1, L2, … , L21), 42 relays (R1, R2, … , R42) and 82 primary and backup relay pairs.

To coordinate the settings of all the 42 relays, there are 84 decision variables, i.e. TDS_1 to TDS_{42} and Ip_1 to Ip_{42}. All buses of the network and DOCRs in Fig. 4 are numbered according to [20]. The TDS_{min} and TDS_{max} limits are 0.1 and 1.1, respectively. The CTI is set to 0.2 s as in

Table 7 Optimal relay settings of 15-bus system

Relay no.	EGWO		GWO	
	*I*p (A)	TDS (*s*)	*I*p (A)	TDS (*s*)
1	235.4227	0.1	318.0214	0.102043214
2	375.5588	0.1	360.9624	0.100163073
3	302.9449	0.108463	376.5405	0.10731513
4	366.9375	0.1	168.9221	0.16787036
5	322.6442	0.108323	129.9544	0.21212723
6	247.4119	0.104738	287.7832	0.104083195
7	274.0357	0.1	223.6695	0.13005814
8	383.6038	0.101471	411.9097	0.124202927
9	229.6315	0.108542	97.54436	0.204986522
10	327.2597	0.1	81.02131	0.221785709
11	388.3736	0.1	378.5692	0.114232976
12	381.9159	0.1	251.7699	0.143648026
13	362.6375	0.1	173.8889	0.173366562
14	417.2187	0.1	120.3426	0.201749458
15	274.6585	0.1	175.5634	0.157519314
16	184.2223	0.1	104.0767	0.153446458
17	137.2422	0.1	47.99683	0.193683149
18	514.7562	0.100251	208.8176	0.169635497
19	312.0396	0.1	160.4151	0.16682298
20	499.7839	0.1	454.6589	0.115977341
21	381.1803	0.1	465.2238	0.120571394
22	147.1611	0.1	104.8691	0.142239368
23	303.329	0.1	366.7312	0.105157907
24	181.6284	0.1	138.6541	0.142671634
25	248.2308	0.1	78.22983	0.214735085
26	202.2457	0.103008	75.11839	0.203230945
27	244.5977	0.1	230.8285	0.126086069
28	261.0349	0.117816	174.8123	0.169640041
29	584.154	0.100006	389.9455	0.144743383
30	147.4626	0.1	53.46232	0.191151213
31	238.4325	0.1	228.9106	0.121165688
32	206.9328	0.1	98.36914	0.184203902
33	292.6497	0.102849	65.78639	0.275329241
34	186.9785	0.112133	114.1267	0.17555259
35	215.8978	0.111206	246.9519	0.119998521
36	297.7092	0.1	359.9366	0.100066772
37	396.0645	0.103148	344.1643	0.135717747
38	199.5016	0.10446	67.03744	0.195255518
39	199.9541	0.101618	68.83235	0.193468459
40	399.5302	0.103143	127.1128	0.223466008
41	188.3151	0.108168	127.5048	0.17364607
42	256.3623	0.1	343.926	0.101302993
$\sum_{i=1}^{N} T_i(s)$	12.22816		15.37621	

Table 8 Primary and backup operating times of relays and CTI of 15-bus system

Relay pairs		T_{Primary} (*s*)	T_{backup} (*s*)	CTI
1	6	0.249181	0.449181	0.2
2	4	0.272528	0.495698	0.22317
2	16	0.272528	0.494986	0.222458
3	1	0.287154	0.536771	0.249618
3	16	0.287154	0.494986	0.207832
4	7	0.275308	0.493119	0.217811
4	12	0.275308	0.514235	0.238927
4	20	0.275308	0.537438	0.26213
5	2	0.31779	0.772418	0.454628
6	8	0.302062	0.502062	0.2
6	10	0.302062	0.570438	0.268376
7	5	0.309853	0.509853	0.2
7	10	0.309853	0.570438	0.260585
8	3	0.276547	0.483017	0.206469
8	12	0.276547	0.514235	0.237688
8	20	0.276547	0.537438	0.26089
9	5	0.290343	0.509853	0.21951
9	8	0.290343	0.502062	0.211719
10	14	0.286065	0.669083	0.383018
11	3	0.283017	0.483017	0.2
11	7	0.283017	0.493119	0.210103
11	20	0.283017	0.537438	0.254421
12	13	0.285155	0.485362	0.200207
12	24	0.285155	0.485262	0.200107
13	9	0.305732	0.505732	0.2
14	11	0.28454	0.517594	0.233054
14	24	0.28454	0.485262	0.200722
15	1	0.239342	0.536771	0.297429
15	4	0.239342	0.495698	0.256355
16	18	0.274028	0.738208	0.46418
16	26	0.274028	0.474028	0.2
17	15	0.260787	0.548261	0.287474
17	26	0.260787	0.474028	0.213241
18	19	0.244088	0.465722	0.221634
18	22	0.244088	0.468236	0.224147
18	30	0.244088	0.450556	0.206468
19	3	0.267524	0.483017	0.215493
19	7	0.267524	0.493119	0.225595
19	12	0.267524	0.514235	0.246711
20	17	0.249488	0.468089	0.218601
20	22	0.249488	0.468236	0.218748
20	30	0.249488	0.450556	0.201068
21	17	0.219551	0.468089	0.248539
21	19	0.219551	0.465722	0.246171
21	30	0.219551	0.450556	0.231005
22	23	0.263952	0.590443	0.326491
22	34	0.263952	0.46898	0.205028
23	11	0.244483	0.517594	0.273111

Table 8 (continued)

Relay pairs		$T_{Primary}$ (s)	T_{backup} (s)	CTI
23	13	0.244483	0.485362	0.240879
24	21	0.26898	0.554535	0.285555
24	34	0.26898	0.46898	0.2
25	15	0.308153	0.548261	0.240108
25	18	0.308153	0.738208	0.430056
26	28	0.289436	0.534823	0.245387
26	36	0.289436	0.525311	0.235875
27	25	0.325311	0.535093	0.209782
27	36	0.325311	0.525311	0.2
28	29	0.355231	0.606658	0.251427
28	32	0.355231	0.569449	0.214218
29	17	0.256296	0.468089	0.211793
29	19	0.256296	0.465722	0.209425
29	22	0.256296	0.468236	0.211939
30	27	0.276945	0.476994	0.200049
30	32	0.276945	0.512142	0.235197
31	27	0.274529	0.476994	0.202465
31	29	0.274529	0.606658	0.332129
32	33	0.297081	0.514939	0.217858
32	42	0.297081	0.547024	0.249943
33	21	0.341683	0.554535	0.212852
33	23	0.341683	0.590443	0.24876
34	31	0.346393	0.565995	0.219602
34	42	0.346393	0.547024	0.200631
35	25	0.334823	0.535093	0.20027
35	28	0.334823	0.534823	0.2
36	38	0.284675	0.484675	0.2
37	35	0.333349	0.533349	0.2
38	40	0.367615	0.567615	0.2
39	37	0.353987	0.553987	0.2
40	41	0.343028	0.543028	0.2
41	31	0.314939	0.565995	0.251055
41	33	0.314939	0.514939	0.2
42	39	0.267186	0.467186	0.2

[9, 20]. Further details of this system such as primary and the backup relationship between relay pairs and fault currents are given in [29].

The optimal values of relay settings obtained by EGWO and GWO are tabulated in Table 7. From this table, it can be noticed that the optimal solution obtained by EGWO is better than that obtained by GWO technique. The operating time of primary and backup relays and CTI value using EGWO are listed in Table 8 and represented graphically in Fig. 10. From Table 8 and Fig. 10, it can be observed that the primary relays operate first and after coordination time margin the backup relays operate in case primary relays failed to isolate the fault. From Tables 7 and 8, it can be observed that the proposed technique satisfies all the constraints of relay setting and coordination constraints associated with primary/backup relay pairs.

The convergence characteristics of EGWO and GWO techniques are shown in Fig. 11. From this figure, it can be noticed that the EGWO technique succeeded in finding the global optimum solution and giving better convergence compared with GWO technique. In addition, it can be noticed that the operating time of all primary relays obtained by EGWO is reduced to 20.47% less than that obtained by the conventional GWO. The required computational time of EGWO is 260 s after 250 iterations, while it is 530 s for GWO after 485 iterations.

The minimum operating time of DOCRs obtained by the proposed technique and other well-known optimization techniques is given in Table 9. From this table, it can be observed that the proposed technique gives the least objective function which confirms its robustness in solving the coordination problem of DOCRs.

4.4 Case 4: IEEE 30-bus test system

The last test system considered in this section is the IEEE 30-bus system [33]. The single-line diagram of IEEE 30-bus network is shown in Fig. 12. In this system, there are 20 lines (L1, L2, … , L20), 38 relays (R1, R2, … , R38) and 62 primary and backup relay pairs.

To coordinate the settings of all the 38 relays, there are 76 decision variables, i.e. TDS_1 to TDS_{38} and Ip_1 to Ip_{38}. All buses of the network and DOCRs in Fig. 10 are numbered according to [33]. The initial ranges for TDS_{min} and TDS_{max} are 0.1 and 1.1, respectively. The PSmin and PSmax limits are 1.5 and 6, respectively, the CT ratio for each relay is 1000:5, and the CTI is set to 0.3 s. Further details of this system such as primary and the backup relationship between relay pairs and fault currents are given in [25].

The optimal values of relay settings obtained by EGWO and GWO are tabulated in Table 10. From this table, it can be noticed that the optimum solution obtained by EGWO is better than that obtained by GWO technique. The operating time of primary and backup relays and CTI value using

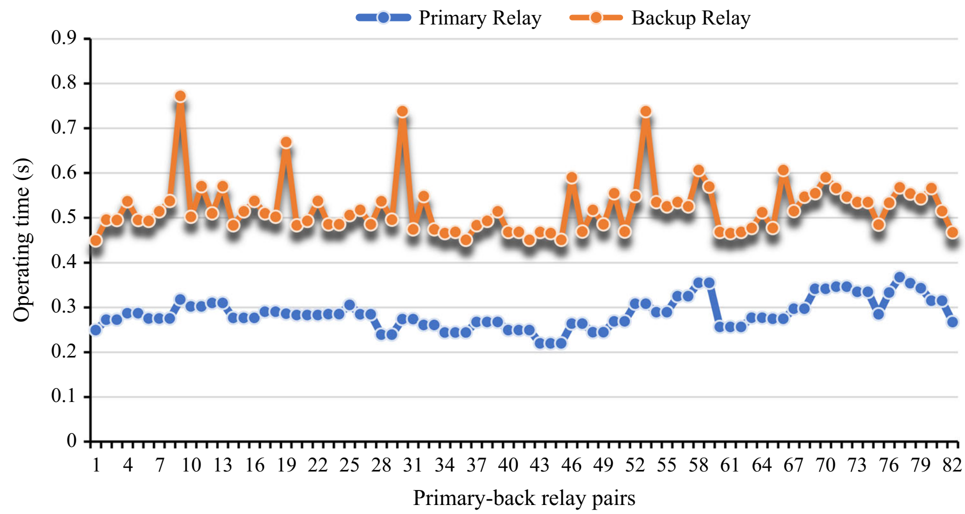

Fig. 10 Operating time of primary–backup relay pairs for 15-bus system

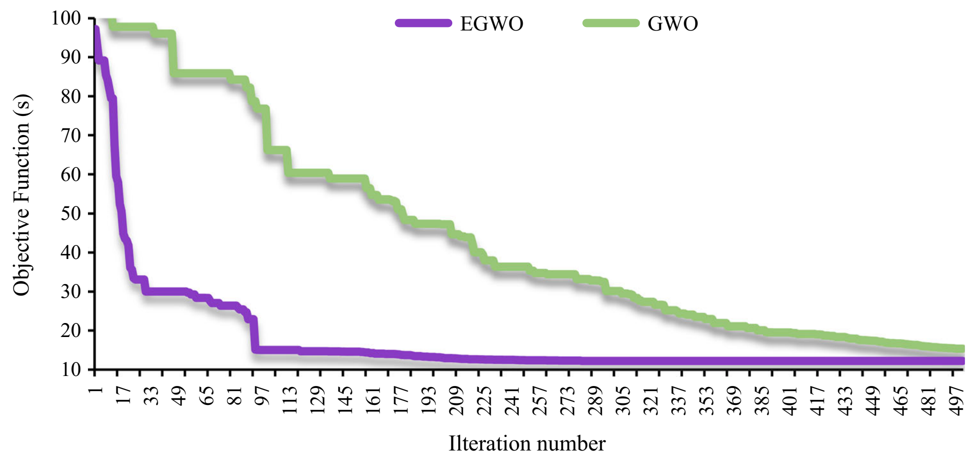

Fig. 11 Convergence characteristics of EGWO and GWO (15-bus system)

Table 9 Minimum operating time of DOCRs obtained by different optimization techniques (15-bus system)

Methods	Objective function (*s*)
EGWO	12.22816
GA	18.9033
PSO	26.8093
MEFO	13.953
HS	19.6165
CSA	19.5521
EFO	17.906
BSA	16.293
EBSA	26.1827
GSO	13.6542
DE	18.9033
MWCA	13.282
WCA	17.728
ER-WCA	15.91

EGWO are listed in Table 11 and represented graphically in Fig. 13.

From Table 11 and Fig. 13, it can be observed that the primary relays operate first and after coordination time margin the backup relays operate in case primary relays failed to isolate the fault. From Table 10 and Table 11, it can be observed that the proposed technique satisfies all the constraints of relay setting and coordination constraints associated with primary/backup relay pairs.

The convergence characteristics of EGWO and GWO techniques are shown in Fig. 14. From this figure, it can be observed that the EGWO technique succeeded in finding the global optimal solution and giving better convergence compared with GWO technique. In addition, it can be noticed that the operating time of all primary relays obtained by EGWO is reduced to 8.4% less than that obtained by the conventional GWO. The required computational time of EGWO is 180 s after 250 iterations, while it is 370 s for GWO after 480 iterations.

The minimum operating time of DOCRs obtained by the proposed technique and other well-known optimization

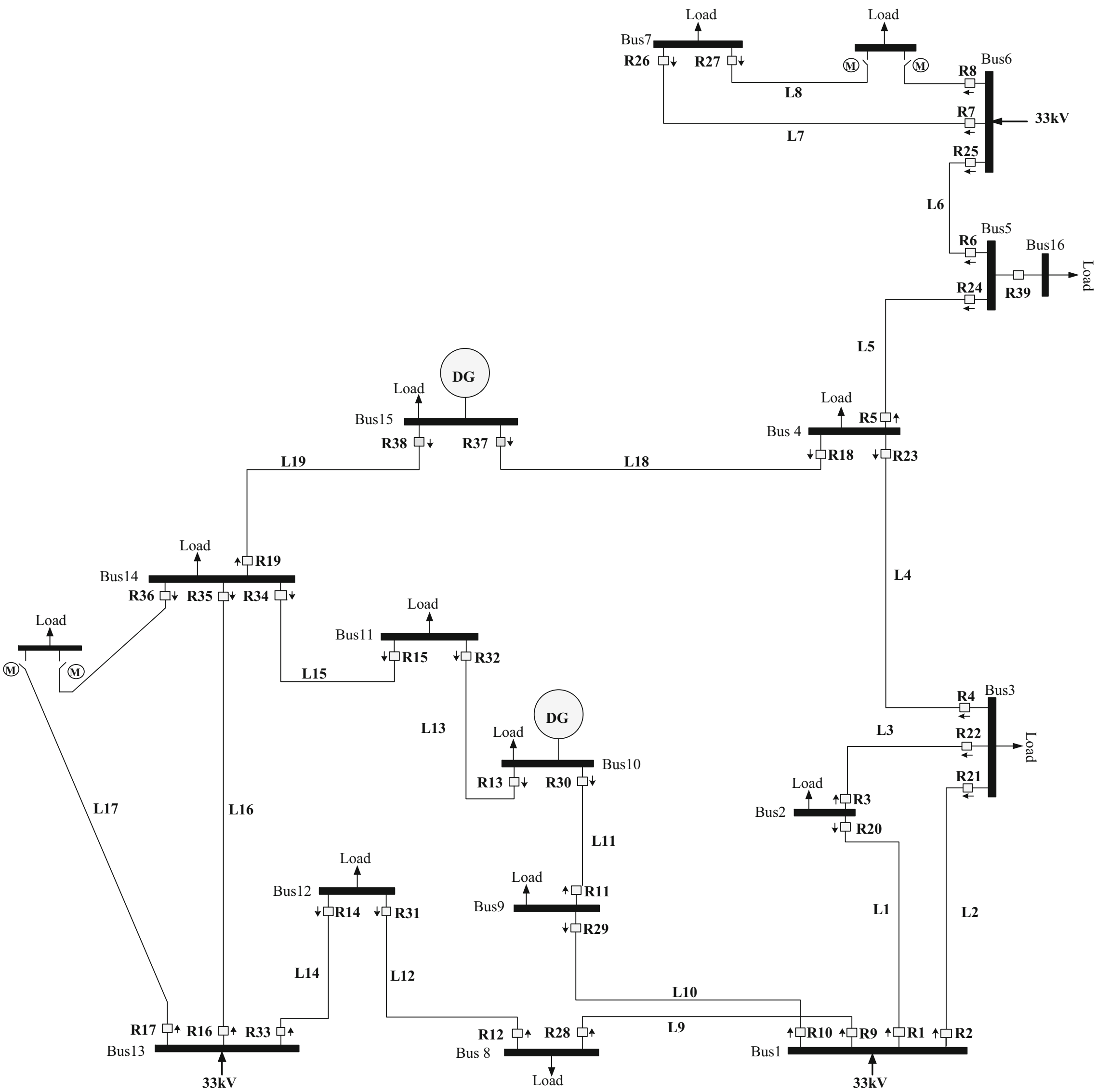

Fig. 12 Single-line diagram of IEEE 30-bus test system

techniques is given in Table 12. From this table, it can be observed that the proposed technique gives the least objective function which confirms its robustness in solving the coordination problem of DOCRs.

4.5 Verification of EGWO using DIgSILENT PowerFactory

DIgSILENT PowerFactory is used to validate the optimal relay settings [39]. Three-phase faults are applied in the different locations along transmission (L20) in 15-bus test system. Three-phase fault occurs near relay no. 39. The operating time of primary and backup relays is shown in Fig. 15. From this figure, it can be observed that the primary relay (relay no. 39) firstly operates and the backup relay (relay no. 37) operates after sufficient time margin (0.2 s), which indicate the correct sequential operation between primary and backup relays.

Three-phase fault occurs near relay no. 40. The operating time of primary and backup relays is shown in

Table 10 Primary and backup operating times of relays and CTI of IEEE 30-bus system

Relay no.	EGWO		GWO	
	PS	TDS	PS	TDS
1	5.497133695	0.154147904	5.070018	0.17349
2	4.709546063	0.102980522	4.121641	0.133244
3	5.134377152	0.121234563	4.813703	0.139867
4	5.799814321	0.100513911	5.243273	0.125237
5	4.560179432	0.102733786	3.260004	0.132855
6	3.3536093	0.102240151	3.444044	0.101775
7	4.431335724	0.1	3.863194	0.105204
8	2.595617396	0.100000006	3.241189	0.102309
9	5.425139417	0.16109172	5.65251	0.181005
10	5.565196773	0.12413914	4.659385	0.165114
11	5.066001018	0.108659257	4.378265	0.145519
12	5.535800612	0.100456678	4.614342	0.131678
13	5.087698647	0.100033712	3.459848	0.13505
14	3.599434298	0.1	3.152613	0.125848
15	3.197384849	0.100000004	3.393969	0.100182
16	5.733555278	0.113023482	3.900225	0.151439
17	2.662121117	0.100000003	2.35608	0.10216
18	4.395698475	0.100000006	3.533533	0.131341
19	4.927251171	0.113948932	4.832471	0.11148
20	2.903927523	0.100000011	2.878013	0.1
21	2.272072409	0.100000598	2.11286	0.106041
22	4.794536696	0.134645795	3.532847	0.16043
23	4.913813992	0.100955289	4.145014	0.131362
24	3.351637775	0.1	2.448781	0.152491
25	3.330089639	0.146125653	1.768964	0.265785
26	2.880613234	0.100005687	1.503689	0.101281
27	2.681289038	0.100000009	2.560487	0.102575
28	3.584444802	0.106064852	3.830094	0.105812
29	3.467778769	0.1	3.527964	0.101603
30	4.739741114	0.101731238	3.507011	0.131815
31	4.158254173	0.100000106	3.836483	0.110504
32	4.049281738	0.102614024	4.182204	0.112782
33	5.074017644	0.121895858	4.355508	0.142737
34	5.345939112	0.106595297	5.080553	0.114862
35	4.170117799	0.100000002	4.29227	0.106815
36	1.710863943	0.100102466	1.585725	0.100258
37	3.833161638	0.100000005	4.283189	0.10023
38	3.742669522	0.100000011	3.323035	0.115968
$\sum_{i=1}^{N} T_i(s)$	17.39405		18.9908	

Table 11 Primary and backup operating times of relays and CTI of IEEE 30-bus system

Relay pairs		T_{Primary} (s)	T_{backup} (s)	CTI (s)
1	21	0.649853	1.619584	0.969731
1	28	0.649853	0.953851	0.303998
1	29	0.649853	1.009805	0.359952
2	20	0.434143	1.167764	0.733621
2	28	0.434143	0.958858	0.524716
2	29	0.434143	1.015626	0.581483
3	1	0.511098	0.811098	0.3
4	2	0.423744	0.871815	0.448071
4	3	0.423744	0.723744	0.3
5	4	0.433103	0.733103	0.3
5	37	0.433103	0.738335	0.305232
6	5	0.431022	0.731022	0.3
7	6	0.421578	0.721578	0.3
8	6	0.421578	0.72834	0.306762
9	20	0.679127	1.083594	0.404468
9	21	0.679127	1.508477	0.82935
9	29	0.679127	1.01152	0.332394
10	20	0.523343	1.095623	0.57228
10	21	0.523343	1.532124	1.008781
10	28	0.523343	0.965262	0.441919
11	10	0.458083	0.758083	0.3
12	9	0.423503	0.723503	0.3
13	11	0.42172	0.72172	0.3
14	12	0.421578	0.721578	0.3
15	13	0.421578	0.721578	0.3
16	14	0.476482	0.826009	0.349528
16	36	0.476482	1.934452	1.45797
17	14	0.421578	0.842505	0.420927
17	35	0.421578	0.851248	0.42967
18	4	0.421578	0.732895	0.311318
18	24	0.421578	0.736931	0.315353
19	15	0.480383	0.797058	0.316675
19	16	0.480383	0.780448	0.300064
19	17	0.480383	1.70536	1.224977
20	22	0.421578	0.721578	0.3
21	3	0.42158	0.729391	0.307811
21	23	0.42158	0.873136	0.451555
22	2	0.567637	0.867733	0.300096
22	23	0.567637	0.867637	0.3
23	24	0.425605	0.733957	0.308352
23	37	0.425605	0.735318	0.309713
24	25	0.421578	0.721578	0.3
26	8	0.421602	1.019318	0.597716
27	7	0.421578	1.372152	0.950574
28	31	0.447146	0.774514	0.327368
29	30	0.421578	0.721578	0.3
30	32	0.428876	0.728876	0.3
31	33	0.421578	0.721956	0.300378
32	34	0.432598	0.732633	0.300035
33	35	0.513886	0.814975	0.301089
33	36	0.513886	1.834612	1.320727
34	16	0.449382	0.781555	0.332173
34	17	0.449382	1.711661	1.262279
34	38	0.449382	0.75017	0.300788
35	15	0.421578	0.793513	0.371935
35	17	0.421578	1.744573	1.322995
35	38	0.421578	0.745909	0.324331
36	15	0.42201	0.807906	0.385897
36	16	0.42201	0.800224	0.378215
36	38	0.42201	0.758596	0.336586
37	19	0.421578	0.721578	0.3
38	18	0.421578	0.723465	0.301887

Fig. 16. From this figure, it can be observed that the primary relay (relay no. 40) firstly operates and the backup relay (relay no. 41) operates after sufficient time margin (0.2 s), which indicates the correct sequential operation between primary and backup relays.

Three-phase fault currents are applied in the middle of transmission line (line no. 20) in 15-bus test system. From Figs. 17 and 18, it can be observed that the operating times of primary relays (relay no. 39 and relay no. 40) are 0.42 s and 0.46 s, respectively, and those of backup relays (relay no. 41 and no. 37) are 0.7 s and 93 s, respectively. In addition, it can be observed that there is sufficient time margin (> 0.2 s) between relay pairs.

5 Conclusion

In this paper, an efficient optimization technique (EGWO) has been proposed and applied to solve the optimal coordination problem of DOCRs. Using the EGWO, the search space and the computation time of the conventional GWO have been reduced by adjusting the parameter which controls the explorative and exploitative phases. The performance of EGWO has been validated and compared with well-established competitive optimization techniques based on four different systems (eight-bus, nine-bus, 15-bus and IEEE 30-bus). The reported results show that the proposed EGWO is able to find the optimal relay setting, maintain the selectivity between relay pairs and converge to the global minimum faster than the

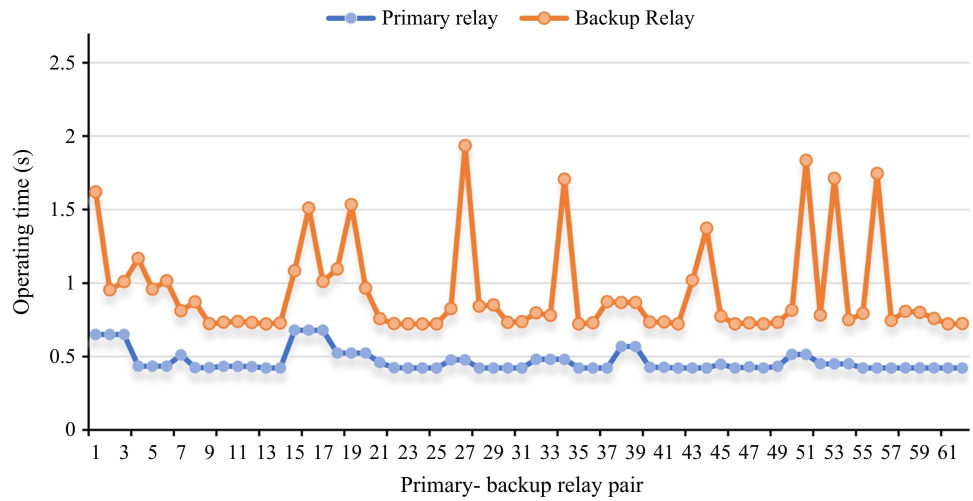

Fig. 13 Operating time of primary–backup relay pairs for IEEE 30-bus system

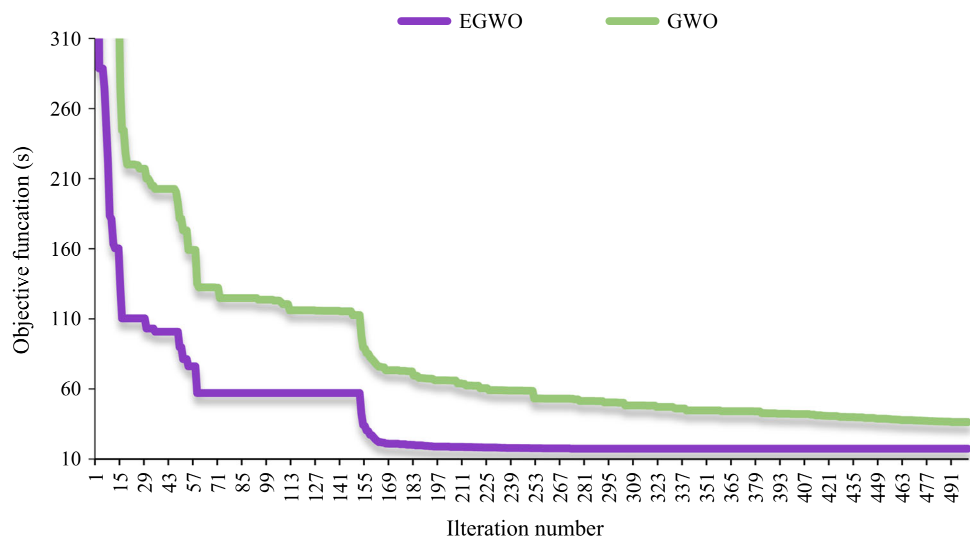

Fig. 14 Convergence characteristics of EGWO and GWO (IEEE 30-bus system)

Table 12 Minimum operating time of DOCRs obtained by different optimization techniques (IEEE 30-bus system)

Methods	Objective function (s)
EGWO	17.39405
GA	28.0195
PSO	39.1836
GSA	51.7747
GSA-SQP	26.8258
SQA	41.0390
DE	17.8122
GS	19.8098
MWCA	19.152
WCA	31.269

conventional GWO. The EGWO technique succeeded in reducing the total operating time of DOCRs (about 19.3995%) to be less than the conventional GWO technique for all test systems. In addition, it noticed that the obtained results using EGWO are better than those obtained by the other optimization techniques. Finally, the results using the EGWO technique have been verified using DIgSILENT PowerFactory. In future, the changes in network topology and the effect of distributed generation on the coordination of DOCRs can be considered. In addition, the proposed optimization technique can be extended to other applications including optimal power flow and optimal allocation of compensation devices to achieve multi-objective functions.

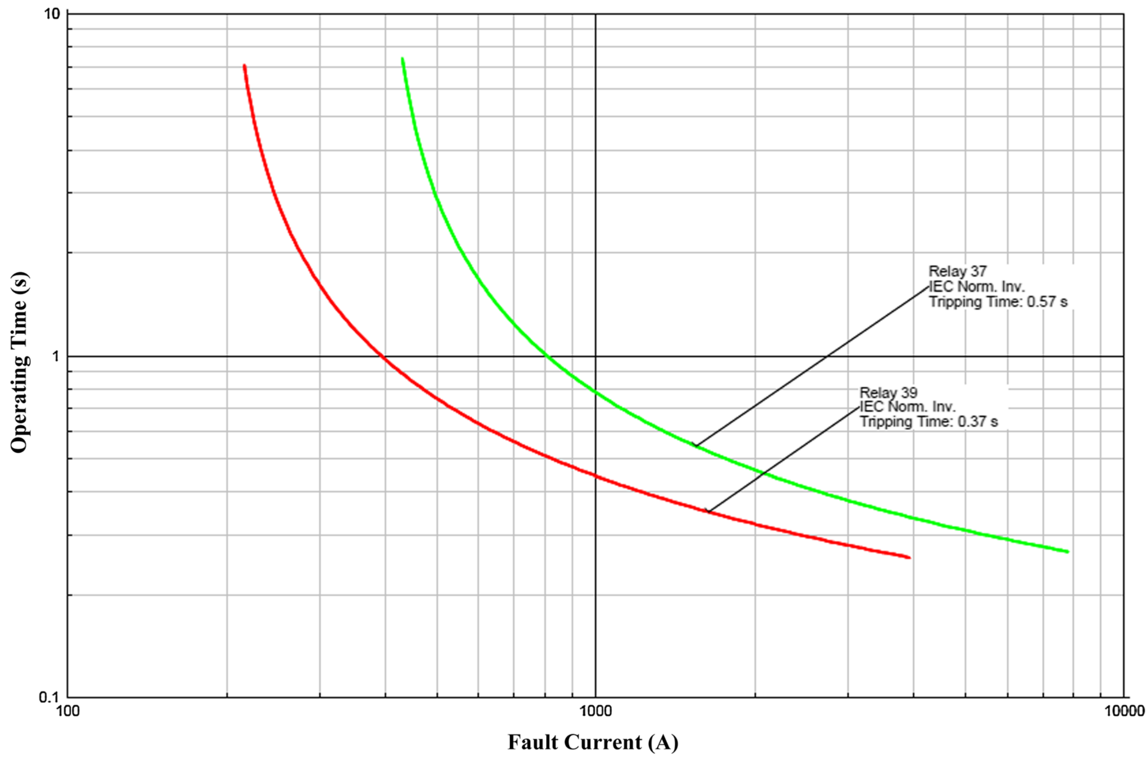

Fig. 15 Operating time of relays 39 and 37 (15-bus system)

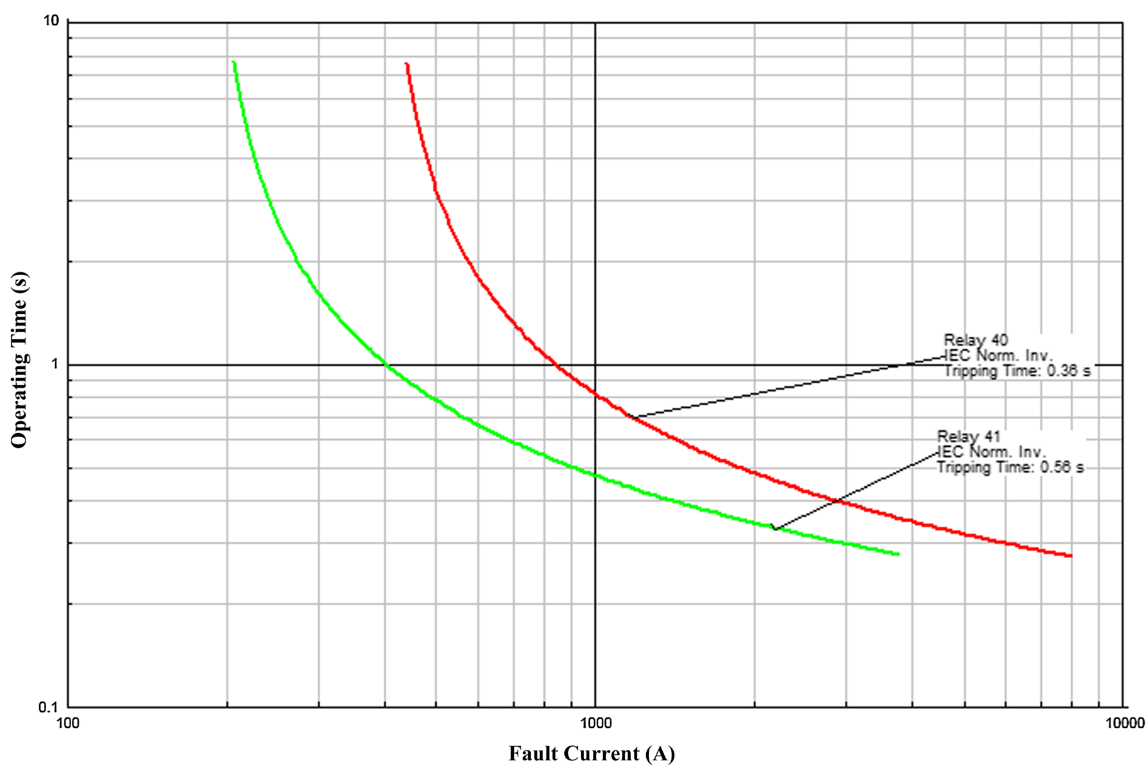

Fig. 16 Operating time of relays 40 and 41(15-bus system)

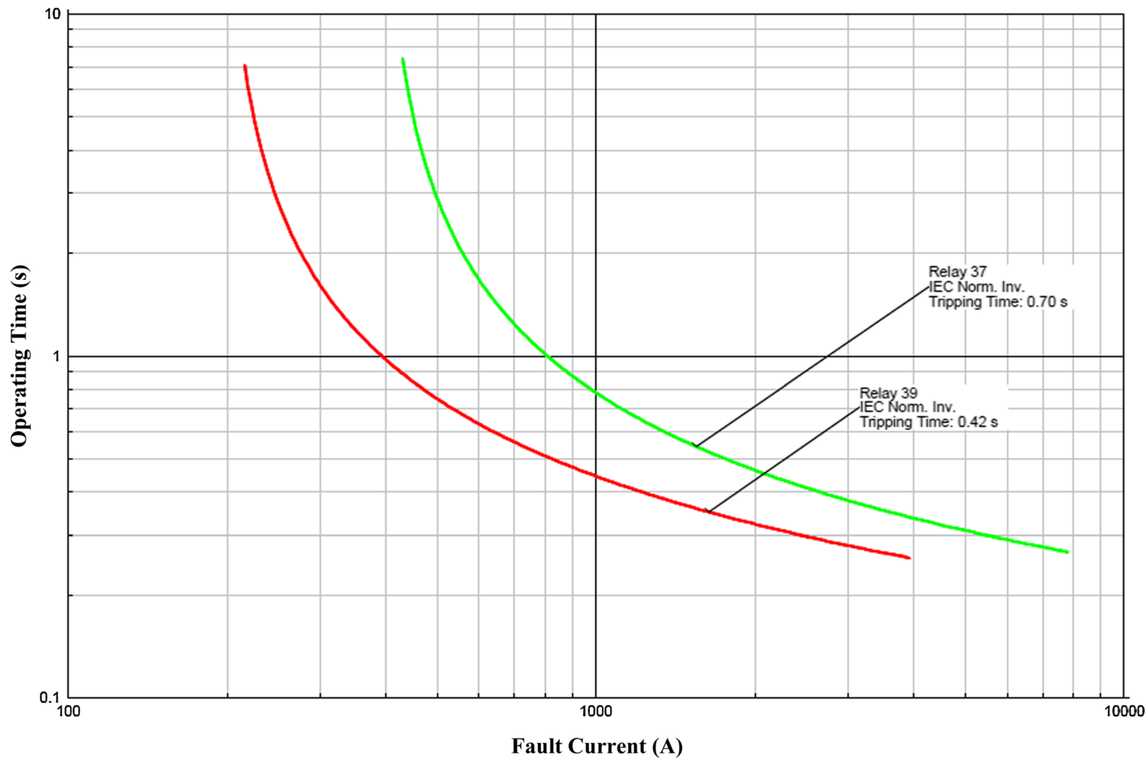

Fig. 17 Operating time of relays 39 and 37 (15-bus system)

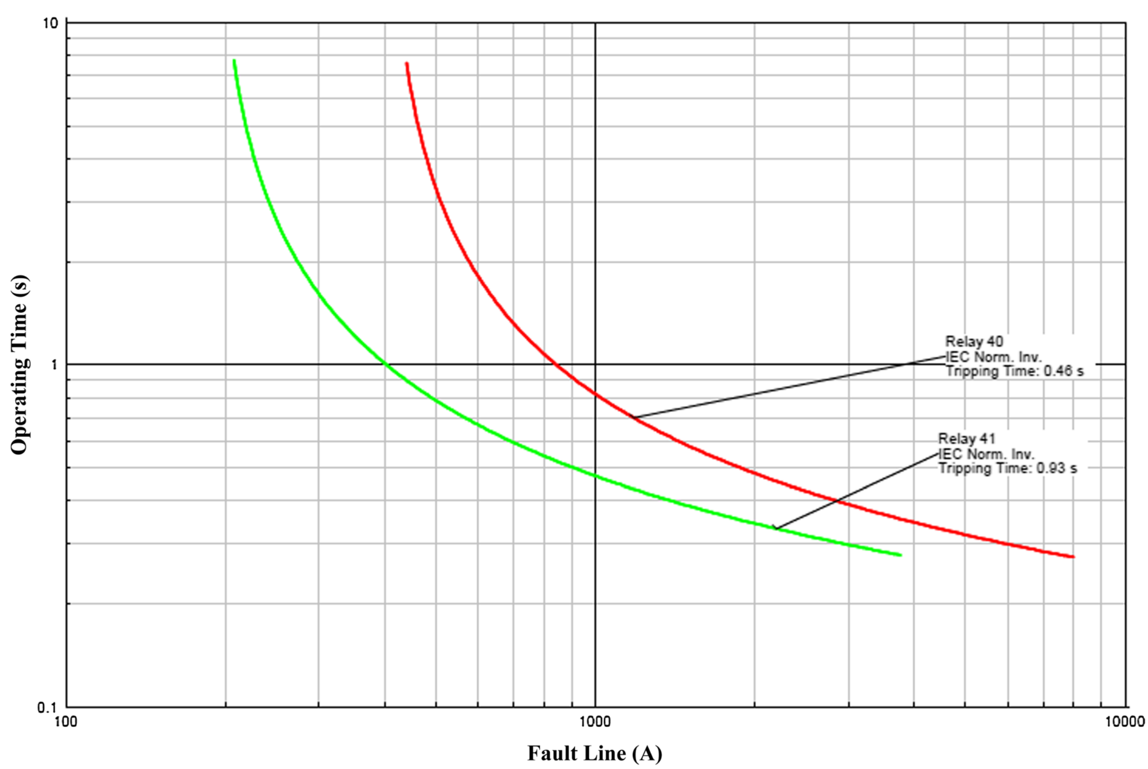

Fig. 18 Operating time of relays 40 and 41(15-bus system)

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