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Optimal coordination of directional overcurrent relays and distance relays using different optimization algorithms

Ahmed Korashy[1] · Salah Kamel[2] · Francisco Jurado[1]

Abstract

The focus of this study is on solving the coordination problem between distance relays (DISRs) and directional overcurrent relays (DOCRs), which is a complex nonlinear problem with various constraints. Ensuring proper coordination between DOCRs and distance relays is critical for maintaining the security of electrical networks. The primary objective of employing optimization algorithms is to determine the optimal operating time for zone-2 of distance relays, as well as the DOCRs setting, time dial setting (TDS), and pickup current (Ipickup). The optimization techniques must also guarantee that the primary and backup relays operate in sequence without any violation. To this end, both recent and well-established optimization algorithms are evaluated using an 8-bus network, with the aim of determining the DOCRs setting and the optimal operating time for zone-2 of distance relays. Furthermore, a comparative analysis of different optimization algorithms, including both traditional and recent techniques, is conducted.

Keywords Distance relays · Directional overcurrent relays · Recent optimization algorithms · Well-known optimization algorithms · Relay settings

1 Introduction

Over the past decade, the electrical network has become increasingly complex, with its size rapidly expanding and the complexity of its operation rising [1]. In order to maintain the security of the electric network at a high level, protective relays play a critical role in isolating fault sections and keeping healthy parts of the network in operation [2]. Sub-transmission and transmission lines are the backbone of the power system, and the use of DOCRs and DISRs is widespread in protecting these lines [3, 4]. The primary protection for DISRs is provided by the first zone, which is set to instantaneously isolate faults on 80–90% of the protected transmission line. The second zone of DISRs serves as backup protection and is responsible for protecting the remainder of the transmission line with an adequate margin [5]. In order to maintain the security of the power network, both DISRs and DOCRs must be properly coordinated. This coordination can be achieved by setting the DOCRs' pickup current, time dial setting (TDS), and operating time of zone-2 for DISRs appropriately.

The coordination problem between DISRs and DOCRs is a complex and nonlinear optimization problem with various constraints [3, 6]. The primary objective of protective relays is to quickly isolate faults in order to minimize the outage of the electric network. If the main relays fail, the backup relays must isolate the faulty sections after a specific coordination time interval (CTI) [7, 8]. Many algorithms have been suggested in the literature to solve the coordination problem for DOCRs, including teaching learning-based optimization (TLBO) [9], Harmony search algorithm (HS) [10], Modified Water Cycle Technique (MWCA) [1], Seeker algorithm [11], BBO-Differential Evaluation (DE) [12], Electromagnetic Field Optimization (EFO) [13], genetic algorithm (GA) [14], Ant colony optimization (ACO) [15, 16], Evaporation Rate Water Cycle Technique [17], and particle swarm optimization

✉ Francisco Jurado
fjurado@ujaen.es

Ahmed Korashy
ahmed.korashy2010@yahoo.com

Salah Kamel
skamel@aswu.edu.eg

1 Department of Electrical Engineering, University of Jaen, EPS, 23700 Linares, Jaén, Spain

2 Electrical Engineering Department, Faculty of Engineering, Aswan University, Aswan 81542, Egypt

(PSO) [18]. However, few algorithms have been proposed to solve the coordination problem for the combined protection scheme of DOCRs and DISRs, such as linear programming (LP) [19], improved seagull optimization algorithm [6], multiple embedded cross-over particle swarm optimization (MEPSO) [20], and modified heap-based optimizer (MHBO) [21]. In this paper, various optimization techniques, including PSO, GA, TLBO, Grey Wolf Optimizer (GWO), Marine Predators Algorithm (MPA), African vulture optimization algorithm (AVOA), Flow Direction Algorithm (FDA), and Gorilla Troops Optimizer (GTO), are proposed to solve the constrained nonlinear coordination problem of DOCRs and DISRs and to obtain optimal settings for coordination.

The primary objective of solving the coordination problem is to minimize the total operating time of zone-2 for DISRs and DOCRs in a combination protection scheme. To ensure proper coordination, various fault positions are simulated to ascertain the time delay between the main and backup relays along the length of the protected line. The efficacy of the proposed optimization algorithms is evaluated on the 8-bus network, and a comparison with recent and established algorithms is performed. The findings reveal that the TLBO algorithm is robust in reducing the operating time of both DOCRs and zone-2 for DISRs, while also resolving the coordination problem. Moreover, the suggested algorithms maintain the correct sequential operation of relay pairs.

2 Problem formulation

DOCRs and DISRs are installed at both ends of the transmission line to protect the electric system. The coordination between the combination of DISRs and DOCRs is considered a non-linear optimization problem. This problem has many limitations. The main goal of solving the coordination problem is to keep the continuity of the electrical networks. This target can be accomplished by getting the DOCRs setting, TDS and Ip, and operating time of zone-2 for DISRs. These settings shall minimize the summation of the operating times for all DOCRs primary relays and operating time for zone-2. Also, the DOCRs setting, TDS and Ip, and operating time of zone-2 for DISRs shall maintain the validation of the sequential operation between relay pairs [22]. The coordination problem of combination distance and directional overcurrent relays is considered a constraint optimization problem [3]. The objective function of the coordination problem of combination DOCRs and DISRs can be described as follows:

$$Minimize\ (Objective\ Function)$$

$$= \sum_{n=1}^{K} Tp_n + \sum_{n=1}^{M} T_{Zone-2_n} \qquad (1)$$

where T_{Zone-2} is the operating time of the zone-2 distance relay, n is the number of relays, K maximum number of DOCRs, and M is the maximum number of distance relays. The T_p is the operating time of primary of DOCRs, which can be described according to IEC-60225 as [1, 2]:

$$Tp_n = \frac{A \times TDS^n}{\left(\frac{I_{fault}^n}{I_{pickup}^n}\right)^B - 1} \qquad (2)$$

$$I_{pickup}^n = CT_{ratio}^n \times PS^n \qquad (3)$$

where A and B are constant and are equal to 0.14 and 0.002, respectively. The I_{fault} is the fault current, CT_{ratio} is the ratio of the current transformer, and PS is the plug setting of relay n [7]. Two categories of constraints; relay characteristics constraints and coordination constraints, shall be maintained during minimising the operating time of all DOCRs primary relays and zone-2 of DISRs.

2.1 Boundaries on DOCRs characteristics and operating time of zone-2

The boundaries of DOCRs settings can be described as follows:

$$Ipickup_{mini}^n \leq Ipickup \leq Ipickup_{maxi}^n \qquad (4)$$

$$PS_{mini}^n \leq PS^n \leq PS_{maxi}^n \qquad (5)$$

$$TDS_{mini}^n \leq TDS^n \leq TDS_{maxi}^n \qquad (6)$$

where $Ipickup_{mini}$ and $Ipickup_{maxi}$ are the boundaries for Ipickup. The TDS_{maxi} and TDS_{mini} are the upper and lower of TDS settings. The range of TDS is based on the DOCRs manufacturer [1]. The Ps_{maxi} and Ps_{mini} are the maximum and minimum range for PS, respectively [1, 2].

The boundary on T_{zone-2} for DISRs can be described as [3]:

$$T_{zone-2_{mini}^n} \leq T_{zone-2}^n \leq T_{zone-2_{maxi}^n} \qquad (7)$$

where $T_{zone-2\ mini}$ and $T_{zone-2\ maxi}$ is the lower and upper limits of operating time for zone-2 of DISRs, respectively.

2.2 Coordination constraints

The coordination time margin (CTI) is required between backup and main relays to maintain system stability. To satisfy the selectivity requirement, the backup relays shall be initiated if the main relays failed to operate as the backup and main relays sense the faults simultaneously [2]. Both DOCRs and DISRs can work as backup or main relays.
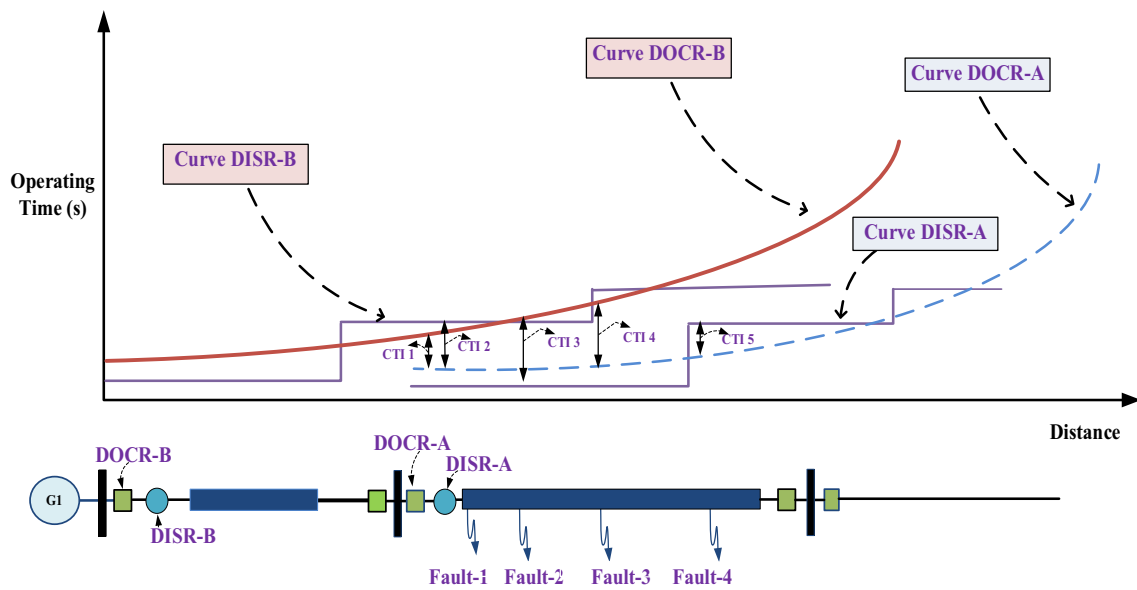
Fig. 1 Coordination between relay pairs
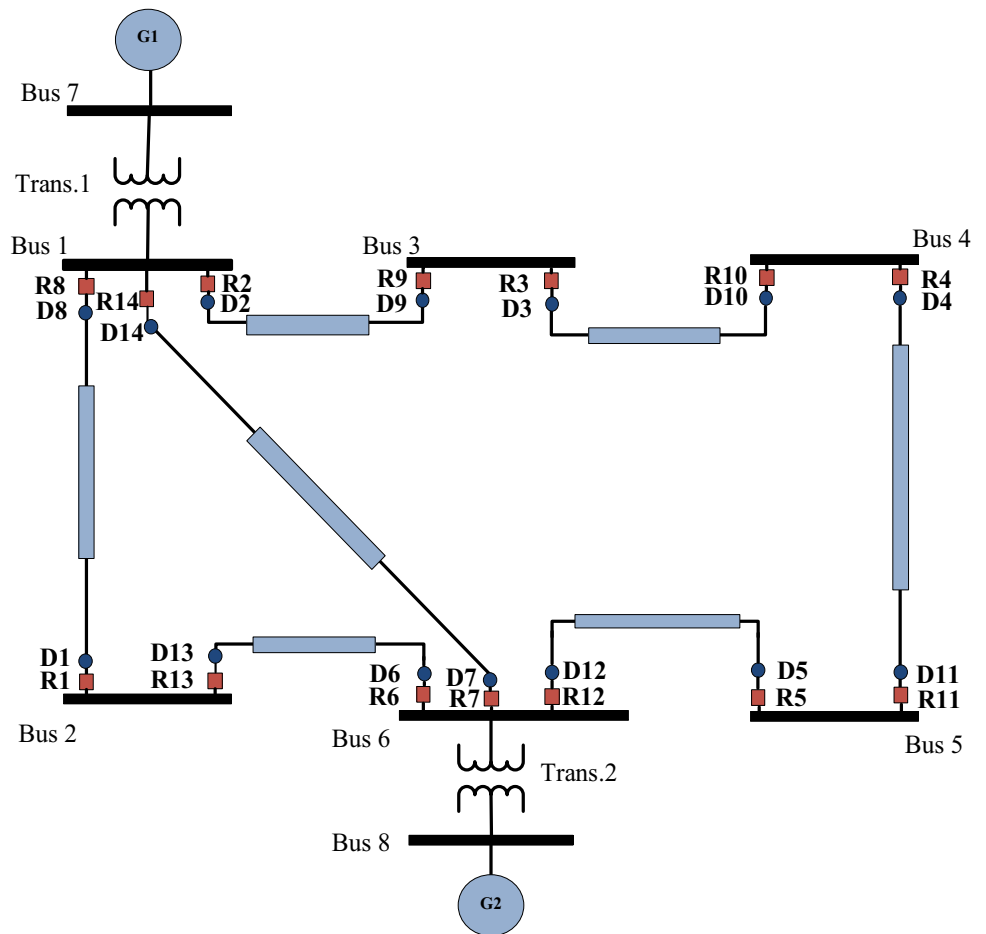
Fig. 2 Single line diagram for 8-bus system

Table 1 Operating time of zone-2 and settings for DOCRs using PSO and GA algorithms

Relay no.	PSO				GA			
	Ip (A)	TDS	Tp(s)	Tzone-2 (s)	Ip (A)	TDS	Tp(s)	TZ2 (s)
1	247.13	0.13	0.37	0.72	232.34	0.14	0.40	0.79
2	466.18	0.19	0.52	0.80	306.83	0.25	0.59	0.87
3	292.21	0.16	0.44	0.70	214.50	0.20	0.50	0.76
4	266.73	0.10	0.33	0.59	203.00	0.14	0.38	0.65
5	236.57	0.06	0.23	0.70	187.03	0.08	0.29	0.72
6	271.34	0.19	0.45	0.72	314.72	0.19	0.47	0.75
7	130.59	0.26	0.50	0.82	207.53	0.23	0.52	0.85
8	205.26	0.18	0.38	0.65	212.59	0.23	0.50	0.79
9	197.90	0.07	0.24	0.69	157.22	0.10	0.32	0.74
10	351.85	0.09	0.33	0.60	291.92	0.12	0.40	0.67
11	207.79	0.19	0.45	0.70	222.36	0.21	0.51	0.77
12	328.68	0.23	0.56	0.82	357.73	0.24	0.60	0.88
13	438.96	0.07	0.27	0.76	211.02	0.16	0.44	0.80
14	230.46	0.21	0.49	0.83	189.69	0.25	0.54	0.88
Objective function	15.67				17.37			

Table 2 Operating time of zone-2 and settings for DOCRs using TLBO and GWO algorithms

Relay no.	TLBO				GWO			
	Ip (A)	TDS	Tp(s)	Tzone-2 (s)	Ip (A)	TDS	Tp(s)	TZ2 (s)
1	449.46	0.06	0.23	0.74	229.43	0.14	0.40	0.82
2	473.11	0.19	0.54	0.83	180.81	0.30	0.60	0.87
3	314.77	0.16	0.47	0.90	89.96	0.27	0.50	0.74
4	477.75	0.08	0.36	0.66	296.06	0.10	0.35	0.62
5	126.52	0.12	0.33	0.65	192.54	0.08	0.27	0.68
6	479.37	0.11	0.32	0.58	410.84	0.17	0.47	0.76
7	314.16	0.17	0.44	0.79	310.84	0.18	0.48	0.83
8	479.93	0.10	0.30	0.58	287.85	0.16	0.38	0.66
9	230.42	0.06	0.21	0.72	199.65	0.07	0.24	0.72
10	478.28	0.07	0.29	0.56	425.52	0.08	0.31	0.59
11	313.48	0.14	0.41	0.66	436.15	0.13	0.41	0.68
12	450.80	0.18	0.51	0.77	137.86	0.30	0.55	0.80
13	479.99	0.06	0.23	0.71	410.15	0.08	0.30	0.75
14	80.25	0.31	0.52	0.82	249.63	0.20	0.48	0.82
Objective function	15.13				16.08			

To maintain proper coordination between relay pairs, coordination should guarantee between DISR to back up DOCRs, DOCRs to backup DISRs, and DOCRs to DOCRs.

As shown in Fig. 1, there are four faults positions, from fault 1 to fault 4, which are considered for coordination between DISRs and DOCRs. For fault1, backup DOCRs shall isolate fault after a time delay in case of main DCRs fail to operate as shown in Fig. 1. This boundary can be expressed as follows:

$$T_{Backup}(F1) - T_{\text{Primary}}(F1) \geq CTI1 \qquad (8)$$

Also, the coordination between the main DOCRs and backup DISRs shall be maintained. This boundary can be expressed as:

$$T_{Zone-2}(F1) - T_{\text{Primary}}(F1) \geq CTI2 \qquad (9)$$

For fault2, main DISRs zone-1 shall clear fault instantaneously and backup DOCR shall operate fault 2 after the time

Table 3 Operating time of zone-2 and settings for DOCRs using MPA and AVOA algorithms

Relay no.	MPA				AVOA			
	Ip (A)	TDS	Tp(s)	Tzone-2 (s)	Ip (A)	TDS	Tp(s)	TZ2 (s)
1	429.15	0.09	0.34	0.79	191.18	0.17	0.44	0.81
2	325.01	0.24	0.59	0.88	303.74	0.25	0.61	0.88
3	276.21	0.19	0.51	0.77	318.10	0.18	0.52	0.79
4	315.14	0.12	0.40	0.76	275.69	0.13	0.42	0.72
5	184.30	0.10	0.32	0.76	126.65	0.12	0.35	0.68
6	478.81	0.15	0.46	0.75	441.79	0.17	0.48	0.78
7	175.39	0.25	0.53	0.87	318.64	0.18	0.48	0.84
8	126.05	0.27	0.49	0.77	462.06	0.14	0.41	0.78
9	161.81	0.10	0.31	0.83	110.14	0.15	0.40	0.75
10	281.23	0.12	0.40	0.67	327.16	0.13	0.45	0.74
11	121.27	0.26	0.52	0.77	479.89	0.15	0.52	0.81
12	410.34	0.23	0.61	0.90	405.77	0.23	0.61	0.88
13	417.29	0.09	0.33	0.82	304.47	0.12	0.38	0.81
14	223.89	0.23	0.53	0.88	316.73	0.19	0.49	0.85
Objective function	17.55				17.65			

Table 4 Operating time of zone-2 and settings for DOCRs using FDA and GTO algorithms

Relay no.	FDA				GTO			
	Ip (A)	TDS	Tp(s)	Tzone-2 (s)	Ip (A)	TDS	Tp(s)	TZ2 (s)
1	303.79	0.11	0.34	0.77	392.35	0.08	0.28	0.78
2	473.42	0.20	0.57	0.86	470.48	0.21	0.58	0.87
3	161.84	0.22	0.50	0.75	225.43	0.21	0.52	0.78
4	217.14	0.13	0.38	0.64	210.70	0.14	0.41	0.67
5	186.73	0.08	0.27	0.67	215.05	0.09	0.32	0.71
6	422.27	0.14	0.40	0.90	169.39	0.25	0.51	0.79
7	289.45	0.18	0.47	0.90	242.10	0.21	0.50	0.84
8	436.93	0.16	0.46	0.88	465.82	0.14	0.41	0.71
9	188.05	0.07	0.25	0.72	144.83	0.11	0.33	0.67
10	328.20	0.10	0.34	0.61	474.71	0.09	0.37	0.66
11	475.32	0.13	0.43	0.70	468.62	0.13	0.46	0.73
12	255.93	0.24	0.55	0.90	474.55	0.19	0.54	0.82
13	248.38	0.13	0.38	0.75	252.58	0.13	0.38	0.83
14	320.00	0.17	0.46	0.85	280.86	0.19	0.47	0.81
Objective function	16.68				16.72			

margin in case of the main relay failed to clear this fault as shown in Fig. 1. This boundary can be formulated as:

$$T_{Backup}(F2) - T_{Zone-1}(F2) \geq CTI3 \tag{10}$$

where TZone-1 is the operating times for main DISR zone-1.

In case of fault happened in fault3, the backup relay DOCR shall isolate fault3 after CTI if the main DOCRs do not succeed to clear the fault. This constraint can be expressed as follows:

$$T_{Backup}(F3) - T_{Primary}(F3) \geq CTI4 \tag{11}$$

For fault 4, backup DISRs shall operate to clear fault 2 after a time delay in case of main DOCRs fails to clear the fault. This constraint can be expressed as follows:

$$T_{Zone-2}(F4) - T_{Primary}(F4) \geq CTI5 \tag{12}$$

The CTI value varies from 0.20 to 0.50 s [1, 2].

Table 5 The operating time of DOCRs obtained using Well-known algorithms

Relay pairs		PSO			GA			TLBO			GWO		
		Tp(s)	Tb (s)	CTI	Tp(s)	Tb (s)	CTI	Tp(s)	Tb (s)	CTI	Tp(s)	Tb (s)	CTI
1	6	0.37	0.57	0.20	0.40	0.60	0.20	0.23	0.43	0.20	0.40	0.62	0.22
2	1	0.52	0.77	0.25	0.59	0.82	0.23	0.54	0.74	0.20	0.60	0.81	0.20
2	7	0.52	0.72	0.20	0.59	0.79	0.20	0.54	0.74	0.20	0.60	0.80	0.20
3	2	0.44	0.64	0.20	0.50	0.70	0.20	0.47	0.67	0.20	0.50	0.70	0.20
4	3	0.33	0.53	0.20	0.38	0.59	0.20	0.36	0.56	0.20	0.35	0.56	0.21
5	4	0.23	0.43	0.20	0.29	0.49	0.20	0.33	0.53	0.20	0.27	0.47	0.20
6	5	0.45	0.70	0.26	0.47	0.71	0.25	0.32	0.66	0.34	0.47	0.68	0.21
6	14	0.45	0.76	0.31	0.47	0.80	0.34	0.32	0.71	0.39	0.47	0.75	0.28
7	5	0.50	0.70	0.20	0.52	0.72	0.20	0.44	0.66	0.22	0.48	0.68	0.20
7	13	0.50	0.76	0.26	0.52	0.81	0.29	0.44	0.71	0.27	0.48	0.80	0.32
8	7	0.38	0.72	0.34	0.50	0.79	0.29	0.30	0.74	0.44	0.38	0.80	0.42
8	9	0.38	0.69	0.31	0.50	0.78	0.28	0.30	0.73	0.42	0.38	0.68	0.30
9	10	0.24	0.44	0.20	0.32	0.52	0.20	0.21	0.41	0.20	0.24	0.44	0.20
10	11	0.33	0.53	0.20	0.40	0.60	0.20	0.29	0.49	0.20	0.31	0.51	0.20
11	12	0.45	0.65	0.20	0.51	0.71	0.20	0.41	0.61	0.20	0.41	0.62	0.21
12	13	0.56	0.76	0.20	0.60	0.80	0.20	0.51	0.71	0.20	0.55	0.80	0.25
12	14	0.56	0.76	0.20	0.60	0.80	0.20	0.51	0.71	0.20	0.55	0.75	0.20
13	8	0.27	0.49	0.22	0.44	0.64	0.20	0.23	0.43	0.20	0.30	0.50	0.20
14	1	0.49	0.77	0.28	0.54	0.82	0.28	0.52	0.75	0.22	0.48	0.81	0.33
14	9	0.49	0.69	0.20	0.54	0.78	0.24	0.52	0.73	0.20	0.48	0.68	0.20

3 Proposed optimization algorithm

3.1 Particle swarm optimization (PSO)

The particle swarm optimization (PSO) algorithm is a population-based stochastic. It is based on swarm theory and it mimics cooperative and social behaviour hunting and navigation of animals as fish schooling to fill their needs. PSO initialized feasible random particles. These particles follow the optimum particles and fly through the problem space. According to its own experience and the experience of nearby particles, the particle modifies its position [23].

3.2 Genetic algorithm (GA)

The genetic algorithm (GA) is based on the natural selection of genes and it mimics Darwinian concepts [12–14]. GA initialize with random solutions, called chromosomes. Genes are encoded into the chromosome. In each iteration genetic principles, crossover and mutation, are applied. Based on the fitness value, the genes are assessed and selected and a new population is formed. The entire cycle is repeated and endeavours to get the optimal solution [24].

3.3 GWO grey wolf optimizer (GWO)

The GWO Grey Wolf Optimizer (GWO) mimics the leadership hunting technique of grey wolves in nature. During a hunt, wolves surround their target and advance to attack. The positions of the prey are better known to the top three wolves. The other wolves update their position based on these three wolves [25].

3.4 Teaching learning-based optimization (TLBO)

Teaching Learning-Based Optimization (TLBO) algorithm is based on the impact of a teacher on students. It mimics the behaviour of teachers and students in a class. A good teacher enhances the performance of learners in class. The students enhance their performance in groups and follow the teacher. Also, students try to improve their performance by interacting with other learners [26].

3.5 Marine predators algorithm (MPA)

Marine Predators Algorithm (MPA) is a population-based technique. It simulates Brownian and Levy motions in ocean predators and has an optimal encounter rate strategy

Table 6 The operating time of DOCRs obtained using recent algorithms

Relay pairs		MPA			AVOA			FDA			GTO		
		Tp(s)	Tb (s)	CTI	Tp(s)	Tb (s)	CTI	Tp(s)	Tb (s)	CTI	Tp(s)	Tb (s)	CTI
1	6	0.34	0.62	0.28	0.44	0.64	0.20	0.34	0.54	0.20	0.28	0.63	0.35
2	1	0.59	1.05	0.46	0.61	0.83	0.22	0.57	0.79	0.22	0.58	0.78	0.20
2	7	0.59	0.80	0.20	0.61	0.81	0.20	0.57	0.77	0.20	0.58	0.78	0.20
3	2	0.51	0.71	0.20	0.52	0.72	0.20	0.50	0.70	0.20	0.52	0.72	0.20
4	3	0.40	0.60	0.20	0.42	0.62	0.20	0.38	0.58	0.20	0.41	0.61	0.20
5	4	0.32	0.54	0.21	0.35	0.56	0.21	0.27	0.48	0.21	0.32	0.52	0.20
6	5	0.46	0.80	0.34	0.48	0.71	0.23	0.40	0.67	0.26	0.51	0.88	0.37
6	14	0.46	0.81	0.35	0.48	0.81	0.33	0.40	0.75	0.34	0.51	0.74	0.23
7	5	0.53	0.80	0.27	0.48	0.71	0.23	0.47	0.67	0.20	0.50	0.88	0.39
7	13	0.53	0.88	0.35	0.48	0.81	0.33	0.47	0.75	0.28	0.50	0.74	0.25
8	7	0.49	0.80	0.30	0.41	0.81	0.39	0.46	0.77	0.31	0.41	0.78	0.37
8	9	0.49	0.77	0.28	0.41	0.81	0.40	0.46	0.69	0.23	0.41	0.76	0.34
9	10	0.31	0.51	0.20	0.40	0.60	0.20	0.25	0.45	0.20	0.33	0.53	0.20
10	11	0.40	0.60	0.20	0.45	0.65	0.20	0.34	0.54	0.20	0.37	0.57	0.20
11	12	0.52	0.72	0.20	0.52	0.72	0.20	0.43	0.63	0.20	0.46	0.66	0.20
12	13	0.61	0.88	0.27	0.61	0.81	0.20	0.55	0.75	0.20	0.54	0.74	0.20
12	14	0.61	0.81	0.20	0.61	0.81	0.20	0.55	0.75	0.20	0.54	0.74	0.20
13	8	0.33	0.61	0.28	0.38	0.58	0.20	0.38	0.64	0.25	0.38	0.58	0.20
14	1	0.53	1.05	0.52	0.49	0.83	0.34	0.46	0.79	0.33	0.47	0.78	0.32
14	9	0.53	0.78	0.24	0.49	0.81	0.32	0.46	0.69	0.23	0.47	0.76	0.29

for predator–prey interactions. Both prey and predator are regarded as search agents. MPA follows the natural laws that control the best foraging technique and encounter ratio between predator and prey in marine ecosystems. At each iteration, the prey is looking for its own food. Also, the predator is looking for its prey. In case of a better predator replaces the top predator, the Elite will be updated [27].

3.6 Flow direction algorithm (FDA)

Flow Direction Algorithm (FDA) is a population-based algorithm. FDA emulates the flow direction to the drainage basin outlet point with the lowest height. In other words, flow moves to the neighbour with the best goal function or lowest high. The quantity of excess or effective rainfall in a drainage basin is the amount of rain that fell but did not percolate into the soil. Direct runoff is actually the quantity of water that remains on the ground surface after precipitation and losses such as interception, evapotranspiration, and infiltration [28].

3.7 African vultures optimization algorithm (AVOA)

African vulture optimization algorithm (AVOA) mimics the navigation and foraging behaviours of African vultures in

nature. The AVOA calculates the objective function of all solutions. Then divide vultures into two categories, where the best solutions are considered as best vultures and other solutions try to follow the best vultures. The worst solution is considered the weakest. The vultures try to follow the best solution and keep away from the worst solution [29].

3.8 Gorilla troops optimizer (GTO)

Gorilla Troops Optimizer (GTO) mimic the collective life of gorillas such as rest, travelling, eating, and talking during the day. GTO is based on the group behaviours of gorillas, who exhibit a variety of methods that are emulated, including migration to an unknown area, migrating to another gorilla, migration in the direction of a defined site, following the silverback, and competing for adult females [30].

4 Results and discussion

The ability of different algorithms in solving the coordination problem of DOCRs and DISRs is assessed in terms of minimising the summation of DOCRs operating time and operating time of zone-2 of DISRs. The proposed algorithms

Table 7 Time margin between relay pairs at different fault locations USING PSO and GA

Relay pairs		PSO				GA			
		Fault1		Fault 2	Fault 3	Fault1		Fault 2	Fault 3
		CTI1	CTI2	CTI3	CTI4	CTI1	CTI2	CTI3	CTI4
1	6	0.20	0.36	0.51	0.24	0.20	0.35	0.55	0.25
2	1	0.25	0.20	0.79	0.51	0.23	0.20	0.84	0.49
2	7	0.20	0.29	0.67	0.27	0.20	0.26	0.76	0.32
3	2	0.20	0.36	0.54	0.22	0.20	0.36	0.60	0.22
4	3	0.20	0.37	0.45	0.22	0.20	0.37	0.51	0.22
5	4	0.20	0.36	0.37	0.25	0.20	0.36	0.43	0.24
6	5	0.26	0.26	1.07	5.27	0.25	0.25	0.90	1.40
6	14	0.31	0.38	0.76	0.55	0.34	0.41	0.81	0.56
7	5	0.20	0.20	5.53	20.00	0.20	0.20	1.80	20.00
7	13	0.26	0.25	3.83	20.00	0.29	0.29	1.19	20.00
8	7	0.34	0.43	0.72	0.56	0.29	0.35	0.82	0.62
8	9	0.31	0.31	1.04	5.83	0.28	0.24	1.01	1.82
9	10	0.20	0.35	0.39	0.28	0.20	0.35	0.47	0.28
10	11	0.20	0.37	0.45	0.21	0.20	0.37	0.52	0.21
11	12	0.20	0.37	0.58	0.22	0.20	0.36	0.64	0.22
12	13	0.20	0.20	0.87	0.78	0.20	0.20	0.80	0.37
12	14	0.20	0.27	0.72	0.30	0.20	0.27	0.76	0.29
13	8	0.22	0.38	0.42	0.23	0.20	0.35	0.58	0.23
14	1	0.28	0.23	1.38	20.00	0.28	0.25	1.40	20.00
14	9	0.20	0.20	3.08	20.00	0.24	0.20	1.80	20.00

have been tested to solve the coordination problem using the 8-bus network. In this paper, the operating for zone-2 limits are 0.2 and 1.5 s [3, 20]. The limit ranges for TDS are 0.05 and 1.1. The CTI1 to CTI 5 is set to 0.2 s [21]. The different fault locations as shown in Fig. 1 are conducted using DigSI-LENT software [31]. A 2.3 GHz PC with 8 GB of RAM and Windows 10 operating systems were used to run the suggested optimization algorithms algorithm in the MATLAB environment.

4.1 8-bus network

Different algorithms are tested on the 8- bus system. As shown in Fig. 2, this system has 7- lines, 14 DOCRs and 14 DISRs, 42 decision variables. The details of this system such as Ipickup ranges are given in [32].

The optimal values of DOCRs settings (Ip and TDS), operating time for primary DOCRs and Tzone-2 for each DISR using PSO, GA, TLBO, and GWO are tabulated in Tables 1 and 2. As shown from this table, the tested optimization algorithms succeed to find DOCRs settings and operating time of zone-2 for distance relays within limit ranges of Ip Ip, TDS, and Tzone-2. The optimal values of Tzone-2 for DISRs,

DOCRs settings, and operating time for primary DOCRs using MPA, AVOA, FDA, and GTO are given in Tables 3 and 4. As shown from this table, the MPA, AVOA, FDA, and GTO algorithms succeed to obtain the operating time of zone-2 and DOCRs settings within the boundaries range of TDS, Ip Ip, and Tzone-2. From Tables 1 and 2, it can be noticed the objective function (15.13 s) by the TLBO algorithm is better than the objective functions that obtained by other algorithms.

The operating time for main and backup DOCRs and time margin using well-known and recent techniques are given in Tables 5 and 6. From these tables, it can be noticed that the primary relays will operate first and the backup relays will operate after discrimination time in case of failure of the primary relay. It can say that the suggested optimization algorithms maintain the sequential operation between primary and backup relays. Where the time difference between the operating time for primary relays and the operating time for backup is greater than the specified coordination time margin (CTI).

The time margin between relay pairs at Fault 1, Fault 2, and Fault 3 using PSO and GA are shown in Table 7. As shown from this table the PSO and GA algorithms succeed to

Table 8 Time margin between relay pairs at different fault locations using TLBO and GWO

Relay pairs		TLBO				GWO			
		Fault1		Fault 2	Fault 3	Fault1		Fault 2	Fault 3
		CTI1	CTI2	CTI3	CTI4	CTI1	CTI2	CTI3	CTI4
1	6	0.20	0.36	0.37	0.25	0.22	0.37	0.57	0.29
2	1	0.20	0.20	0.95	1.25	0.20	0.22	0.83	0.47
2	7	0.20	0.24	0.73	0.36	0.20	0.23	0.79	0.38
3	2	0.20	0.36	0.57	0.23	0.20	0.37	0.60	0.22
4	3	0.20	0.54	0.49	0.21	0.21	0.39	0.47	0.21
5	4	0.20	0.33	0.51	0.36	0.20	0.35	0.41	0.27
6	5	0.34	0.33	0.72	0.80	0.21	0.22	0.87	1.43
6	14	0.39	0.51	0.67	0.51	0.28	0.35	0.76	0.53
7	5	0.22	0.21	1.04	20.00	0.20	0.20	1.83	20.00
7	13	0.27	0.26	11.48	20.00	0.32	0.27	2.86	20.00
8	7	0.44	0.48	0.81	0.91	0.42	0.45	0.88	0.93
8	9	0.42	0.42	1.36	20.00	0.30	0.34	1.03	6.41
9	10	0.20	0.35	0.38	0.32	0.20	0.35	0.39	0.31
10	11	0.20	0.37	0.41	0.21	0.20	0.37	0.44	0.22
11	12	0.20	0.37	0.53	0.22	0.21	0.39	0.54	0.21
12	13	0.20	0.20	0.85	0.93	0.25	0.20	0.90	0.76
12	14	0.20	0.32	0.64	0.24	0.20	0.27	0.71	0.31
13	8	0.20	0.35	0.37	0.25	0.20	0.35	0.44	0.22
14	1	0.22	0.22	20.00	20.00	0.33	0.34	1.37	20.00
14	9	0.20	0.20	20.00	20.00	0.20	0.24	3.17	20.00

Table 9 Time margin between relay pairs at fault 4 using well-known algorithms

Primary (DOCR)	Backup zone-2	PSO Fault 4 CTI 5	GA Fault 4 CTI 5	TLBO Fault 4 CTI 5	GWO Fault 4 CTI 5
1	1	0.20	0.20	0.37	0.27
2	2	0.20	0.20	0.20	0.20
3	3	0.20	0.29	0.37	0.20
4	4	0.35	0.20	0.21	0.20
5	5	0.20	0.20	0.20	0.29
6	6	0.20	0.21	0.20	0.20
7	7	0.20	0.28	0.20	0.20
8	8	0.33	0.20	0.20	0.20
9	9	0.20	0.20	0.39	0.37
10	10	0.20	0.20	0.20	0.21
11	11	0.20	0.21	0.20	0.20
12	12	0.33	0.20	0.20	0.20
13	13	0.20	0.20	0.34	0.28
14	14	0.20	0.20	0.20	0.20

Table 10 Time margin between relay pairs at different fault locations using MPA and AVOA

Relay pairs		MPA				AVOA			
		Fault1		Fault 2	Fault 3	Fault1		Fault 2	Fault 3
		CTI1	CTI2	CTI3	CTI4	CTI1	CTI2	CTI3	CTI4
1	6	0.28	0.42	0.58	0.35	0.20	0.34	0.60	0.28
2	1	0.46	0.20	1.33	1.71	0.22	0.20	0.84	0.44
2	7	0.20	0.27	0.76	0.31	0.20	0.23	0.80	0.38
3	2	0.20	0.37	0.61	0.22	0.20	0.36	0.62	0.21
4	3	0.20	0.37	0.53	0.22	0.20	0.36	0.55	0.22
5	4	0.21	0.44	0.49	0.30	0.21	0.37	0.51	0.29
6	5	0.34	0.30	1.01	1.57	0.23	0.20	0.78	0.70
6	14	0.35	0.42	0.82	0.60	0.33	0.37	0.85	0.66
7	5	0.27	0.22	1.97	20.00	0.23	0.20	1.13	20.00
7	13	0.35	0.28	3.38	20.00	0.33	0.33	1.56	20.00
8	7	0.30	0.37	0.82	0.60	0.39	0.42	0.89	0.91
8	9	0.28	0.34	1.02	1.99	0.40	0.33	0.94	1.13
9	10	0.20	0.35	0.46	0.27	0.20	0.34	0.57	0.31
10	11	0.20	0.38	0.51	0.20	0.20	0.35	0.59	0.24
11	12	0.20	0.37	0.65	0.23	0.20	0.36	0.65	0.21
12	13	0.27	0.21	1.00	0.85	0.20	0.20	0.84	0.48
12	14	0.20	0.27	0.77	0.30	0.20	0.24	0.78	0.33
13	8	0.28	0.44	0.54	0.28	0.20	0.40	0.53	0.27
14	1	0.52	0.26	13.03	20.00	0.34	0.31	1.27	20.00
14	9	0.24	0.30	1.88	20.00	0.32	0.25	1.33	20.00

maintain the sequential operation relay pairs without any violation. As time margin between the main and backup relays at the different fault locations is greater than the specified margin.

The coordination time margins at Fault 1, Fault 2, and Fault 3 using TLBO and GWO are given in Table 8. From this table, it can be noticed that the TLBO and GWO algorithms succeed to keep sequential operations without any miscoordination between relay pairs. As time margin between the main and backup relays at the different fault locations is greater than the specified margin.

The CTI at Fault 4 using PSO, GA, TLBO and GWO are given in Table 9. From this table, it can be observed that the time margin between the main and backup relays is greater than the specified time delay. From Tables 7 and 9, it can be noticed that tested optimization algorithms maintain the coordination between primary and backup relays along protected transmission lines.

The coordination time margins at Fault 1, Fault 2, and Fault 3 using MPA and AVOA are given in Table 8. From this table, it can be noticed that the MPA and AVOA algorithms succeed to keep sequential operations without any miscoordination between relay pairs. As time margin between the main

and backup relays at the different fault locations is greater than the specified margin.

The time margin between relay pairs at Fault 1, Fault 2, and Fault 3 using FDA and GTO are shown in Table 11. As shown from this table FDA and GTO algorithms succeed to maintain the sequential operation relay pairs without any violation. As time margin between the main and backup relays at the different fault locations is greater than the specified margin.

The CTI at Fault 4 using MPA, AVOA, FDA, and GTO are given in Table 12. From this table, it can be observed that the time margin between the main and backup relays is greater than the specified time delay. From Tables 10 and 12, it can be noticed that tested optimization algorithms maintain the coordination between primary and backup relays along protected transmission lines.

From Tables 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, it can be noticed that the proposed optimization techniques satisfy all the boundaries of DISRs and DOCRs and settings and keep the discrimination between primary ad backup relays at the different fault locations.

The convergence curve of the suggested algorithms is shown in Fig. 3. From this figure, it can be observed that the TLBO algorithm obtained the optimal relay settings and

Table 11 Time margin between relay pairs at different fault locations using FDA and GTO

Relay pairs		FDA				GTO			
		Fault1		Fault 2	Fault 3	Fault1		Fault 2	Fault 3
		CTI1	CTI2	CTI3	CTI4	CTI1	CTI2	CTI3	CTI4
1	6	0.20	0.56	0.49	0.26	0.35	0.51	0.56	0.38
2	1	0.22	0.20	0.85	0.59	0.20	0.20	0.92	0.87
2	7	0.20	0.33	0.75	0.35	0.20	0.26	0.76	0.33
3	2	0.20	0.36	0.60	0.23	0.20	0.36	0.62	0.23
4	3	0.20	0.37	0.50	0.21	0.20	0.37	0.53	0.22
5	4	0.21	0.37	0.42	0.26	0.20	0.36	0.46	0.24
6	5	0.26	0.26	0.83	1.34	0.37	0.20	1.24	3.04
6	14	0.34	0.45	0.78	0.66	0.23	0.29	0.76	0.51
7	5	0.20	0.20	1.68	20.00	0.39	0.22	3.46	20.00
7	13	0.28	0.28	1.20	20.00	0.25	0.33	1.21	20.00
8	7	0.31	0.44	0.83	0.75	0.37	0.43	0.83	0.74
8	9	0.23	0.26	0.99	3.51	0.34	0.26	0.94	1.52
9	10	0.20	0.36	0.40	0.28	0.20	0.33	0.51	0.36
10	11	0.20	0.36	0.47	0.23	0.20	0.36	0.50	0.22
11	12	0.20	0.46	0.55	0.20	0.20	0.36	0.58	0.22
12	13	0.20	0.20	0.74	0.40	0.20	0.28	0.74	0.39
12	14	0.20	0.31	0.72	0.33	0.20	0.26	0.71	0.31
13	8	0.25	0.50	0.59	0.33	0.20	0.33	0.53	0.27
14	1	0.33	0.31	1.80	20.00	0.32	0.32	3.83	20.00
14	9	0.23	0.26	2.44	20.00	0.29	0.20	1.56	20.00

Table 12 Time margin between relay pairs at fault 4 using recent algorithms

Primary (DOCR)	Backup Zone-2	MPA Fault 4 CTI 5	AVOA Fault 4 CTI 5	FDA Fault 4 CTI 5	GTO Fault 4 CTI 5
1	1	0.25	0.21	0.28	0.35
2	2	0.21	0.20	0.20	0.20
3	3	0.20	0.20	0.20	0.20
4	4	0.28	0.22	0.20	0.20
5	5	0.28	0.20	0.27	0.23
6	6	0.20	0.20	0.41	0.20
7	7	0.20	0.20	0.28	0.20
8	8	0.20	0.27	0.32	0.20
9	9	0.38	0.20	0.35	0.20
10	10	0.20	0.20	0.20	0.20
11	11	0.20	0.20	0.20	0.20
12	12	0.21	0.20	0.29	0.20
13	13	0.31	0.27	0.22	0.30
14	14	0.21	0.20	0.25	0.20

Fig. 3 Objective function of the different optimization algorithms
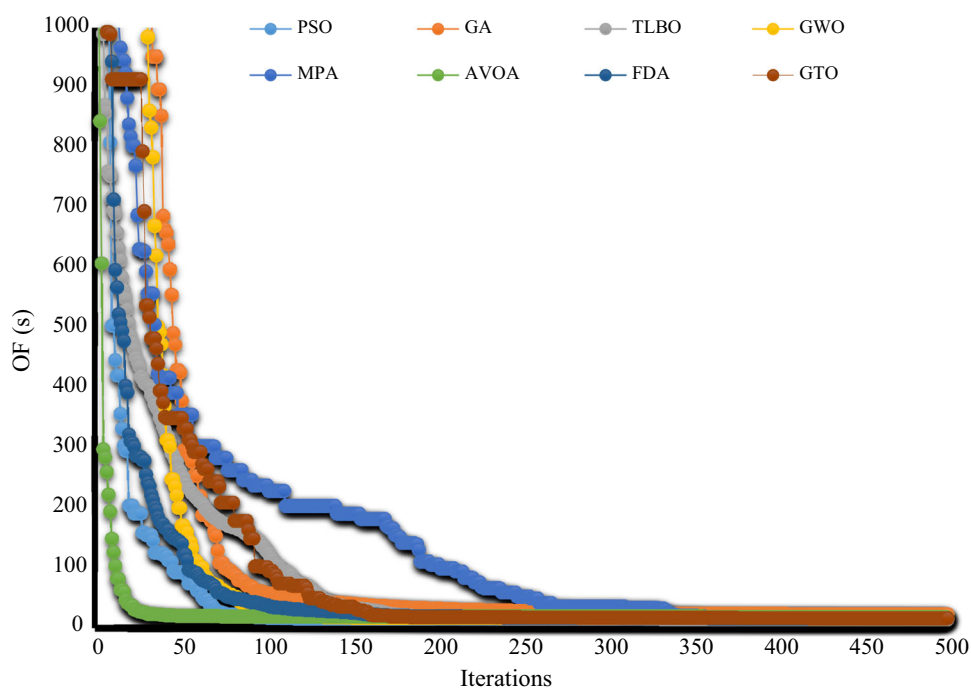
Table 13 Comparison between well-known and recent optimization algorithms

Methods	Objective function (s)
PSO	15.67
GA	17.37
TLBO	15.13
GWO	16.08
MPA	17.55
AVOA	17.65
FDA	16.68
GTO	16.71

reached better convergence compared with other optimization algorithms. Where the OF value using TLBO (15.13 s) is less than the other optimization techniques.

The comparison between recent and well-known algorithms for solving the coordination problem of DOCRs in combination with DISRs is shown in Table 13. The obtained results from this table show that the total operating times of DOCRs and the total operating zone-2 of DISRs using the TLBO algorithm are lower than those computed by other algorithms.

5 Conclusion

In conclusion, this paper tackled the challenging nonlinear coordination problem between DOCRs and DISRs using a variety of optimization algorithms, including PSO, GA, TLBO, GWO, MPA, AVOA, FDA, and GTO. The goal was to minimize the total operating time of DOCRs and Tzone-2 of DISRs while maintaining the selectivity between relay pairs. The performance of these algorithms was evaluated on an 8-bus system, and a comparison between recent and traditional optimization algorithms was conducted to identify the most competitive techniques. The results demonstrated the effectiveness of the proposed optimization algorithms in maintaining selectivity between relay pairs without any violation. Moreover, the TLBO algorithm outperformed other optimization methods, achieving better convergence and obtaining the optimal relay settings with a lower objective function value.

Declarations

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