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Optimal Coordination of Directional Overcurrent Relays (DOCR) Using Cheetah Optimizer

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Keywords:

Directional overcurrent relays; Nature-inspired algorithm; Optimization algorithm; Optimal coordination; Protection.

Highlights:

- *Optimal Coordination of DOCRs represents an important issue in power system protection.*
- *Nature-inspired strategies are proposed to overcome the lack of traditional methods.*
- *Various recent counterparts' strategies were proposed for optimal coordination problems.*
- *Optimal Coordination of DOCRs was performed using MATLAB 2023 b.*

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Abstract: This paper suggests a nature-inspired optimization technique, the Cheetah Optimizer (CO), to achieve optimal Directional Overcurrent Relays (DOCRs) coordination. The main contribution of this work is proposing a recent effective optimization technique (CO) for optimal coordination of DOCRs to clear the faults in the power system as soon as possible. CO strategy can solve nonlinear, non-convex complex coordination problems to achieve a fast and selective protection system. CO has advanced features overcoming other strategies, such as fast convergence, lower computational time, moderate exploration and exploitation modes, and attaining the optimal solution, avoiding stuck in local optima. Three test systems were used in this work. The standard IEEE-3, IEEE-9, and IEEE-30 bus test systems were used to confirm the performance of the proposed technique. The results yielded by the proposed algorithm were compared with other recently established counterparts, such as the Chimp Optimization Algorithm (ChOA), Osprey Optimization Algorithm (OOA), Coati Optimization Algorithm (COA), Seagull Optimization Algorithm (SOA), and Pelican Optimization Algorithm (POA). The proposed technique's reliability, stability, and consistency were recognized by inclusive statistical analysis. The proposed approach offered high-quality and robust solutions with lower computational processing times. In addition, it has a remarkable convergence, giving a benefit over adaptive coordination tendency by improving monitoring, communication, and grid control.

التنسيق الأمثل لمرحلات التيار المفرط الاتجاهية باستخدام تقنية أمثلية الفهد

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الخلاصة
في هذا البحث تم اقتراح تقنية تحسين مستوحاة من الطبيعة، وهي تقنية أمثلية الفهد (CO)، لتحقيق التنسيق الأمثل لـمرحلات التيار المفرط الاتجاهي. أن الهدف الرئيسي من هذا العمل هو اقتراح تقنية أمثلية حديثة وهي تقنية (CO) وذلك للتنسيق الامثل لمرحلات التيار الاتجاهي المفرط لازالة الاخطاء من منظومات القدرة بالسرعة الممكنة. تستطيع تقنية (CO) حل المشاكل المحدبة المعقدة واللاخطية لتنسيق للمرحلات للحصول على نظام حماية انتخابي سريع. تمتلك تقنية (CO) عدة مميزات متقدمة على باقي التقنيات الاخرى مثل، تقارب سريع للوصول الى الحل، زمن تنفيذ سريع للخوارزمية، طريقة بحث واستكشاف متوازنة، أمكانية الوصول الى الحل الامثل دون الوقوع في الأمثلية المحلية. تم استخدام ثلاثة أنظمة اختبار قياسية في هذا العمل وهي IEEE-3 bus systems وIEEE-9 وIEEE-30. تم مقارنة النتائج التي أسفرت عنها الخوارزمية المقترحة مع نظيراتها الأخرى التي تم إكتشافها مؤخرًا مثل خوارزمية أمثلية الشمبانزي (ChOA)، وخوارزمية أمثلية العقاب (OOA)، وخوارزمية أمثلية حيوان القوطي (COA)، وخوارزمية أمثلية النورس (SOA)، وخوارزمية أمثلية البجع (POA). تم التعرف على موثوقية واستقرار واتساق التقنية المقترحة من خلال التحليل الإحصائي الشامل. قدمت التقنية المقترحة حلولاً قوية وعالية الجودة مع أوقات معالجة حسابية أقل. فضلاً عن ذلك فهي تتمتع بخواص تقارب ملحوظ، مما يعطي فائدة على التنسيق التكيفي من خلال تحسين المراقبة والاتصالات والتحكم في الشبكة.

الكلمات الدالة: مرحلات التيار المفرط الاتجاهي، خوارزمية مستوحاة من الطبيعة، خوارزمية أمثلية، التنسيق الامثل، الحماية.

1.INTRODUCTION

The coordination of Directional Overcurrent Relays (DOCRs) represents an active issue in distribution and transmission networks. The researchers pay great attention to optimal relay coordination. Optimal coordination of DOCRs aims to find a suitable relay pickup current setting (PCS) and time dial setting (TDS), considering various constraints. The DOCRs coordination has been considered an optimization problem. This optimization problem can be solved using multiple traditional and heuristic strategies. The power system is susceptible to irregularities that must be removed to avoid power system instability and damage to permanent types of equipment [1-4]. Typically, a power system comprises many segments, and each part must be protected from overcurrent. Recently, protection systems have earned importance in the interconnected distribution system [5-7]. After occurring the fault, the main target of the power system protection is to separate the minimum number of network segments instantly [8]. Maintaining the power system selectivity (switching off faulted parts and avoiding switching off unfaulted elements) is crucial to confirming optimum supply reliability. Overcurrent relays are sufficient for radial systems with single feeding points and unidirectional power flow to obtain the desired selectivity. In contrast, they are insufficient for multisource issues radial systems and closed ring topology systems due to bidirectional power flow. In these cases, DOCRs are used due to their ability to detect the overcurrent polarity [5, 9]. To achieve a fast and selective protection system, DOCRs should be optimally coordinated [10]. The main target in DOCRs coordination is to attain the suitable time dial setting (TDS) and pickup current setting (PCS) of relays, maintaining several system constraints, like boundary limits and coordination [11, 12]. Before a relay operates, the TDS regulates time delay if a sensed fault current reaches a value equal to or exceeds the pickup current. The PCS defines a relay pickup current that passes through it. The PCS value is expressed as a multiple of the current transformer's nominal current. These parameters specify the DOCRs time–current characteristic [1]. The DOCRs coordination has been regarded as a complex nonlinear optimization problem and solved using conventional and heuristic techniques [13, 14]. Nevertheless, conventional optimization approaches have a problem; sometimes, they may fail to reach the global optimal solution and trap local minima, as they have a weak convergence as the system size increases. Heuristic techniques can overcome these disadvantages with less computation time, especially with non-convex problems [13, 15]. In most academic fields, resolving optimization issues has recently emerged as a challenging and attractive topic. Various heuristic optimization techniques have recently been utilized to solve complex constraints and nonlinear, non-convex characteristics [16-19]. Various population-based metaheuristic techniques have recently been utilized to solve nonlinear, non-convex, complex-constrained DOCRs coordination problems. A literature review of the last five years is presented in this work to clarify the DOCRs coordination complicated problem. Several population-based approaches have been established in the related works. The Firefly Algorithm (FA) is used to coordinate DOCRS optimally based on its PCS while keeping TDS constant [11]. A Gravitational Search (GS) based algorithm is presented for obtaining optimal coordination of DOCRS based on various standard test systems, such as 8, 15, and 30 bus systems [14]. The coordination problem is formulated using Whale Optimization Algorithm (WOA). The algorithm performance is tested on various test systems, such as 3, 8, 9, 14, 15, and 30 bus test systems. [12], A Genetic Algorithm (GA) is proposed while its performance is tested on the standard IEEE 8 node benchmark [20]. Enhanced Version of Grey Wolf Optimizer (EGWO) is used to solve the coordination problem to minimize the relays' total operation time [21]. Fractional Particle Swarm and Gravitational Search Algorithm (FPSOGSA) is used to improve the coordination problem and implemented on standard IEEE 3, 8, and 15 bus networks [10]. Modified African Vultures Optimization Algorithm (MAVOA) [13] and Hybridized Version of Particle Swarm Optimization (HPSO) [22] are used for solving P/B relay coordination problems in power systems. Hybrid Firefly Algorithm-Linear Programming (FA-LP) is fulfilled to coordinate the relays optimally by attaining its TDS and PCS, considering all constraints. The proposed approach is verified on the IEEE 8, 15, and 30-node systems. [5]. The DOCR coordination problem is optimized using a Hybrid Firefly–Genetic Algorithm (FA-GA). The proposed algorithm is tested on various standard test systems [23]. The main contributions of this study are to propose an efficient modern metaheuristic algorithm known as the Cheetah Optimizer (CO) for solving nonlinear, non-convex complex DOCRs coordination problems to achieve a fast and selective protection system. This technique has many advantages: fast convergence, lower computation time, fine exploration features, and attaining the optimal solution avoiding entrap in local optima. Three test systems (the standard IEEE-3, IEEE-9, and IEEE-30 bus test systems) were utilized in this paper to confirm the performance of the proposed technique. The results yielded by the proposed algorithm were compared with other recently proposed algorithms such Chimp Optimization Algorithm (ChOA), Osprey Optimization Algorithm (OOA), Coati Optimization Algorithm (COA), Seagull Optimization Algorithm (SOA), and Pelican Optimization Algorithm (POA). The present work compared the proposed algorithm with more than six modern metaheuristic algorithms to support the obtained results.

2.PROBLEM FORMULATION

The critical target of solving the DOCR coordination problem is maintaining power system security and reliability. This aim can be attained by finding the optimal settings of TDS and PCS for relay [21]. The protection zone of the DOCR represents the fault current function. The relay will start as the measured fault current exceeds the predetermined PCS. In DOCRs coordination, all installed relays must offer primary protection of their line and backup protection for all adjacent lines [1].

2.1.Objective Function

The primary relay (PR) is the fictional relay to operate first for fault clearing. Conventionally, the objective function (OF) in coordination problems is established as the summation of all PRs operating times (OTs). Therefore, the OF may be expressed as follows [5]:

$$\min_{PCS_i, TDS_i} OF = \sum_{i=1}^{m} \sum_{k} T_{ik} \quad \textbf{(1)}$$

Regarding the operating DOCR characteristics, the formula used to define the time-current curvatures, according to International Electrotechnical Commission (IEC) IDMT Standard 60255-151 (see Table 1), are [1, 5]:

$$T_{ik} = \frac{\alpha \times TDS_i}{\left(\frac{I_{ik}}{PCS_i}\right) - 1} \quad \textbf{(2)}$$

Table 1 IEC Standard Characteristics for the Overcurrent Relays.

Characteristic	Long time inverse	Extremely inverse	Very inverse	Normally inverse
α	120	80	13.5	0.14
n	1	2	1	0.02

Each relay uses one current transformer (CT) to reduce and withstand the current level. It is necessary to define the primary rating of CT in the problem. $I_{f\ ik}$ is the fault current at the primary terminals of CT, and CT_{rating} is the rating of CT. The fault current seen by the relay (I_{ik}) is as follows:

$$I_{ik} = \frac{I_{f,ik}}{CT_{rating}} \quad \textbf{(3)}$$

2.2.Bounds of Settings

When the current reaches a value equal to or greater than the pickup current setting, the TMS controls the time delay before the relay operates. The minimum PCS should equal or exceed 1.25 times the maximum load current to ensure the relay does not malfunction under average load or slight overload conditions. Similarly, to ensure the relay is responsive to the slightest fault current, the maximum pickup setting should be less than or equal to 2/3 times the minimum fault current [23, 24]. The limits of the settings can be expressed as:

$$TDS_i^{\min} \le TDS_i \le TDS_i^{\max}, \quad i = 1,\dots,m \quad \textbf{(4)}$$

$$PCS_i^{\min} \le PCS_i \le PCS_i^{\max}, \quad i = 1,\dots,m \quad \textbf{(5)}$$

The PCS_i must exceed the maximum load current and be lower than the minimum fault current seen by individual relays, including the protection limit. This protection limit depends on CT errors and the relay technology [12].

2.3.Bounds of Relay Operating Time

The limits of OTs for each relay can be expressed as:

$$T_{ik}^{\min} \le T_{ik} \le T_{ik}^{\max}, \quad i = 1,\dots,m \quad \textbf{(6)}$$

The relay manufacturing specifies the lower operation time limit of the ith relay. In contrast, the critical clearing time required to prevent equipment damage and maintain the system's stability specifies the upper limit of operation time of the ith relay [5].

2.4.Coordination Criteria

In the overcurrent protection scheme, if the primary relay fails to operate, then the corresponding backup relay operates instead to protect the power system types of equipment. To confirm proper relay coordination, the backup relay OT should exceed the corresponding primary relay for all the faults occurrence [21, 24]. Coordination time interval (CTI) is expressed as follows:

$$CTI = T_{jk} - T_{ik}, \qquad i = 1, \ldots, m \qquad (7)$$

All primary/backup (P/B) pairs of relays must be satisfied by the constraints. For the majority of fault scenarios, fault currents for far-end, near-end, and mid-point are often utilized to provide coordination. The constraint of the CTI can be formulated as:

$$CTI \geq CTI_{\min} \qquad (8)$$

2.5.Objective Function of CTI Minimization

Due to the nonlinear nature of the relay, the objective function (OF), coordination constraints, and operating time constraints become nonlinear in the coordination problem of DOCRs. Since many linear and nonlinear constraints exist, the coordination problem is called a complicated and nonlinear optimization problem. Evolution for the OF should be carefully planned to create a workable solution that satisfies these restrictions [24]. For good selectivity, it is desired to maintain a minimum CTI between the P/B pair of relays. From the viewpoint of proper relay coordination, considerably delayed operation of backup relays is not desirable. Expression for OF is modified to optimize the CTI between P/B relays.

$$\min_{PCS_i, TDS_i} MOF = \alpha_1 \sum_{i=1}^{m} \sum_{k} T_{ik}^{\,2} + \alpha_2 \sum_{p=1}^{m_p} \left[\Delta T_{mbp} - \beta \left(\Delta T_{mbp} - \left| \Delta T_{mbp} \right| \right) \right]^2 \qquad (9)$$

$$\Delta T_{mbp} = T_{jk} - T_{ik} - CTI \qquad (10)$$

Miscoordination is reduced; however, relay OTs are increased by raising β. As a result, the appropriate β is fitted to a value that omits the miscoordination [1, 5].

3.CHEETAH OPTIMIZER (CO)

Several swarm intelligence approaches are inspired by animals' social hunting and foraging behaviors in nature [25, 26]. In some cases, and during the hunting process, several hunter members can hunt the prey in the herd with some members or independently, so not all hunting members participate in the hunting process. Therefore, a small number of hunters can cover a large hunting area effectively, representing superior features of the cheetah hunting process. The cheetah is regarded as the fastest land mammal. It is a giant cat breed predator living in Asia and Africa [27, 28]. The cheetah optimization algorithm CO is a metaheuristic algorithm recently proposed by Akbari et al. (2022) [28]. The CO is inspired by the hunting approaches of cheetahs in the wild. CO is a meta-heuristic population-based algorithm where the velocity and location of the cheetahs or prey are definite in the search space. The CO is imitated by the four hunting strategies of cheetahs in the wild: Searching; Sitting-and-waiting; Attacking, this strategy has two essential steps: rushing and capturing; and leaving the prey and going back home [29, 30].

3.1.Search Strategy

Cheetahs search prey using one of two modes; either scanning the land while standing or sitting or the surrounding area using active patrols. The active mode requires more energy than the scan mode. The first mode is more proper for dense and grazing prey, whereas walking on the plains. Instead, the second mode is more suitable for scattering and active prey. To formulate this search strategy for cheetahs, the following search formula is used for updating the cheetah's new position, as follows [28]:

$$X_{i,j}^{t+1} = X_{i,j}^{t} + r_{i,j}^{-1} . \alpha_{i,j}^{t} \qquad (11)$$

The step length value can be set at (0.001t/T) in case of a slow walking search of cheetahs. The cheetahs may escape quickly and change their direction while encountering other enemies. The randomized parameters are chosen for each cheetah in different hunting periods. The position of the leader cheetah is updated by setting the randomized parameter equal to (0.001t/T) and multiplying it by the maximum step size. While the position updating of other cheetahs is done by multiplying the distance between the position of an ith member and a randomly selected member [28, 29].

3.2.Sit-and-Wait Strategy

The prey may become exposed to a cheetah's field of view during the searching mode. Every cheetah movement in this scenario could alert the prey to its existence and cause the prey to escape. Therefore, to avoid the prey running, the cheetah may ambush to get close enough to the prey by sitting on the ground or lurking in the bushes. As a result, in this phase, the cheetah waits for the prey to come nearer while maintaining their position. This behavior can be expressed as [28]:

$$X_{i,j}^{t+1} = X_{i,j}^{t} \quad (12)$$

To increase hunting success, i.e., find a better solution, this strategy must refrain from changing all cheetahs simultaneously in each group, helping the algorithm avoid premature convergence.

3.3.Attack Strategy

Speed and flexibility are two essential factors that cheetahs use to assault their prey. A cheetah runs to the prey at full speed when it decides to attack. The prey eventually becomes aware of the cheetah's attack and runs away [28, 30]. The cheetah swiftly chases the prey in the line of interception. In other words, the cheetah tracks the prey's location and modifies its course to block the prey's path at a certain point. The prey must flee and change its location quickly to survive because the cheetah has only traveled a short distance from it at excessive speed. Additionally, the single cheetah likely does not engage in an offensive tactic that perfectly replicates its natural hunting behavior. During this stage, the cheetah captures the prey by moving quickly and maneuvering around. Each cheetah in a pack may alter its position in response to the movement of the prey and that of the leader or other nearby cheetahs. These strategies are defined as follows:

$$X_{i,j}^{t+1} = X_{B,j}^{t} + \check{r}_{i,j} \cdot \beta_{i,j}^{t} \quad (13)$$

Compared to hunting techniques, the proposed CO approach only requires a few equations to describe the hunting process. To avoid premature convergence in the various optimization problems, these strategies establish an appropriate trade-off between the exploration and exploitation phases [28]. The CO algorithm is illustrated in the flow chart in Figure 1.

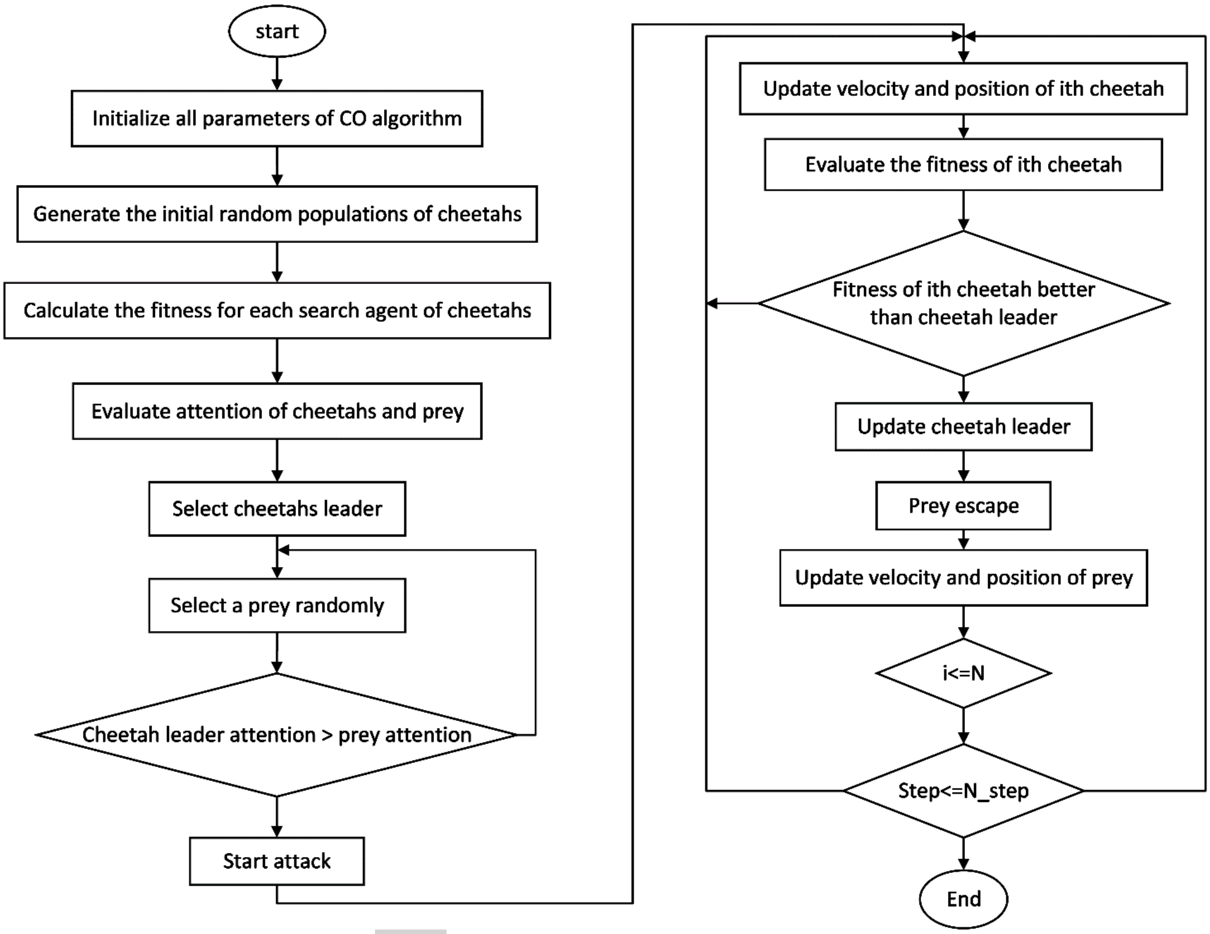


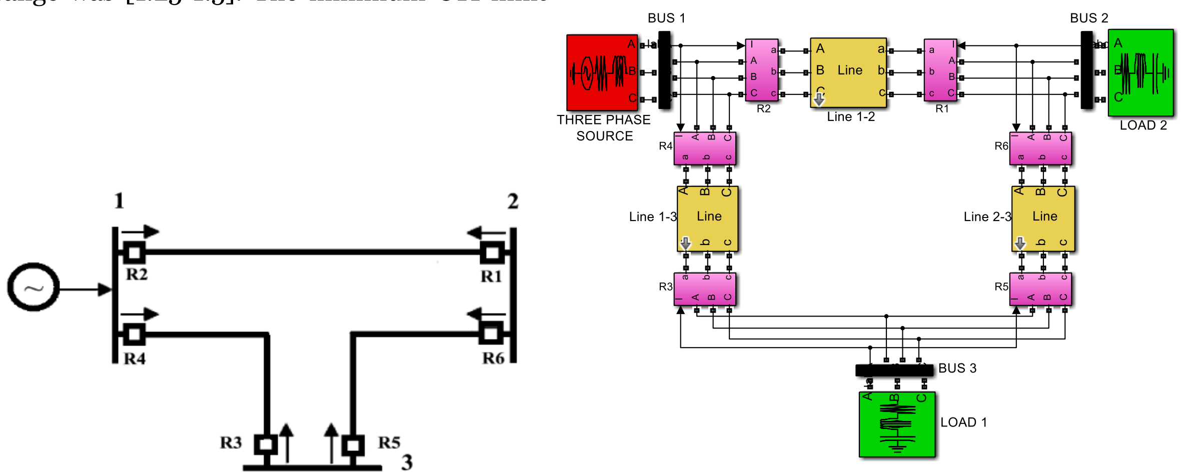
Fig. 1 Flow Chart of the CO Algorithm.

4.SIMULATION AND RESULTS

The proposed CO algorithm was simulated over three standard test systems, i.e., standard IEEE-3, IEEE-9, and IEEE-30 bus, with six, twenty-four, and thirty-eight DOCRs, respectively. The typical test systems are extensively used as benchmarks for solving the DOCR coordination problem. The results yielded by the proposed algorithm were compared with other recent optimization algorithms, such as Chimp Optimization Algorithm (ChOA), Osprey Optimization Algorithm (OOA), Coati Optimization Algorithm (COA), Seagull Optimization Algorithm (SOA), and Pelican Optimization Algorithm (POA). The proposed algorithms parameters used for this work were adopted as follows: 50 iteration number and 30 population size, except CO was chosen as two cheetahs and six prey. All used test systems were considered with DOCRs having the inverse typical characteristics (α = 0.14 and n = 0.02).

4.1. Test System 1

This test system is the standard IEEE 3-bus test system, as shown in Fig. 2. This system includes 6 DOCRs. The main target is to coordinate all the relay settings, adjusting to clear all far- and near-end faults. It was found twelve probable decision variables (2 decisions for each relay). The TDS limits were [0.05-1.1], while the PCS range was [1.25-1.5]. The minimum CTI limit was adjusted to its typical value of 0.30 s. Tables 2 and 3 provide further information, such as the CT ratings and the I_f determined for all P/B relays for far- and near-end faults. The optimal TDS and PCS values of the proposed approach were compared with results from other metaheuristic strategies, as displayed in Table 4. Table 4 contains the OTs of all P relays for far- and near-end faults. The OTs were within the accepted range [0.1–1.1 s]. Table 5 demonstrates no miscoordination pairings when the DOCRs were in operation.



(a) Schematic diagram. (b) Simulink model.

Fig. 2 Test System 1.

Table 2 Fault Currents Value for Test System1 [31, 32].

Relay NO.	Fault current Near-end I_f	Near-end CTI	Far-end I_f	Far-end CTI	Line
1	9.46	2.06	14.08	2.06	1-2
2	29.91	2.06	100.63	2.06	1-2
3	8.81	2.23	12.07	2.23	1-3
4	37.68	2.23	136.23	2.23	1-3
5	17.93	0.8	25.9	0.8	2-3
6	14.35	0.8	19.2	0.8	2-3

Table 3 Fault Currents for P/B Relays in Test System 1 [31, 32].

Primary relay NO.	Fault current Near-end I_f	Near-end CTI	Far-end I_f	Far-end CTI	Backup relay NO.	Fault current Near-end I_f	Near-end CTI	Far-end I_f	Far-end CTI
1	9.46	2.06	14.08	2.06	5	9.46	0.8	14.08	0.8
3	8.81	2.23	12.07	2.23	6	8.81	0.8	12.07	0.8
5	17.93	0.8	25.9	0.8	4	17.93	2.23	25.9	2.23
6	14.35	0.8	19.2	0.8	2	14.35	2.06	19.2	2.06

Table 4 Results for Test System 1.

		R1	R2	R3	R4	R5	R6	OF(s)
FAGA [23]	TDS	0.100069	0.100000	0.100022	0.100033	0.100000	0.100000	1.365040
	PCS	1.945890	1.500000	1.787530	1.683100	1.500000	1.500050	
MFA [23]	TDS	0.100000	0.100000	0.100000	0.100000	0.100000	0.100000	1.413850
	PCS	2.226550	1.503510	2.512020	1.692690	1.737000	1.500000	
WOA [12]	TDS	0.050000	0.050000	0.055530	0.050000	0.071000	0.158700	1.526200
	PCS	1.250000	1.250000	1.383700	1.250000	2.474600	2.216300	
FPSOGSA [10]	TDS	0.100100	0.101300	0.100700	0.101200	0.100200	0.100300	1.461700
	PCS	2.500000	2.000000	3.000000	2.500000	2.500000	1.500000	
ChOA	TDS	0.050000	0.215700	0.050000	0.231000	0.194400	0.194500	1.484100
	PCS	1.376900	1.321500	1.346200	1.267600	1.340700	1.335800	
OOA	TDS	0.050000	0.217600	0.050000	0.275100	0.252900	0.193600	1.370400
	PCS	1.374900	1.276000	1.267300	1.264400	1.255200	1.292000	
COA	TDS	0.071200	0.489000	0.060700	0.430200	0.423500	0.310500	1.273500
	PCS	1.396300	1.308100	1.301000	1.343700	1.287000	1.411100	
SOA	TDS	0.071700	0.472000	0.130400	0.386000	0.340200	0.444900	1.179800
	PCS	1.455800	1.367800	1.285300	1.363700	1.366700	1.377400	
POA	TDS	0.050000	0.372800	0.050400	0.229400	0.187200	0.260300	1.196300

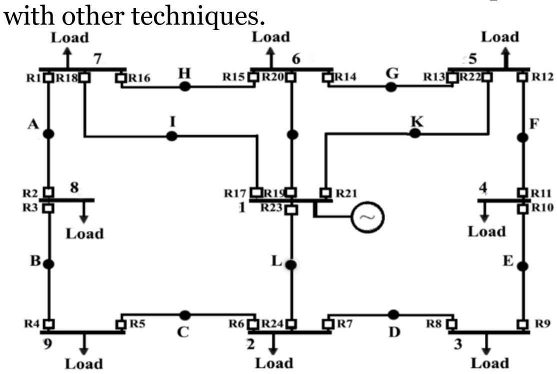
	PCS	1.411100	1.250400	1.371000	1.294100	1.500000	1.252100	
CO	TDS	0.050000	0.224200	0.050000	0.265400	0.209900	0.203100	0.670300
	PCS	1.287800	1.265000	1.419200	1.422900	1.324900	1.260300	
	OT near end	0.271800	0.656700	0.338400	0.732500	0.505000	0.521200	
	OT far end	0.206200	0.414100	0.258000	0.475900	0.445200	0.468300	

Table 5 CTI Ratings for Test System 1.

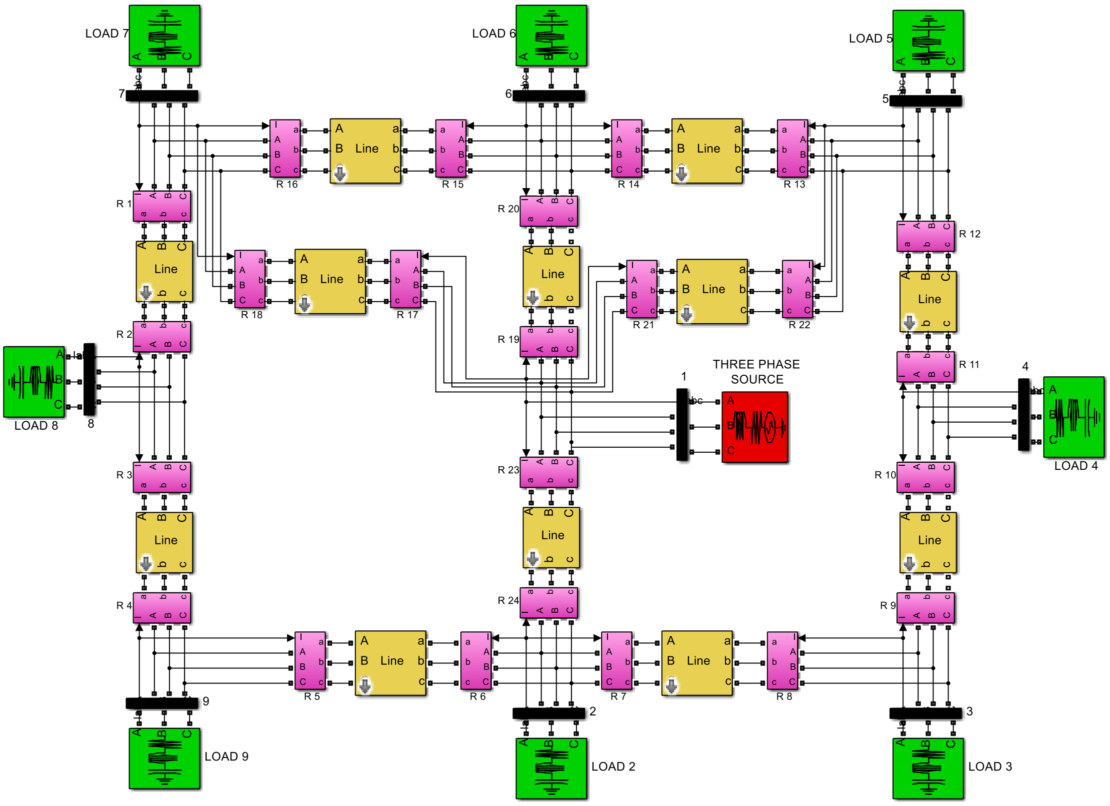
Fault	Relay		CTI	Fault	Relay		CTI
	Primary	Backup			Primary	Backup	
Near-end	1	5	0.3000	Far-end	1	5	0.3362
	3	6	0.3000		3	6	0.3212
	5	4	0.3000		6	2	0.4004
	6	2	0.3901		5	4	0.3000

4.2. Test System 2

The considered benchmark in this section is the standard 9-bus test system, as shown in Fig. 3. This test system had 24 digital DOCRs. The TDS limits were [0,01 – 1], while the PCS range was [0.5 - 2.5]. The CTI_{min} value was adjusted at 0.2 s, and each relay's CT ratio was 500/1. Faults caused by short-circuiting occurred on the center of the individual line and were pedantic from A to L, as illustrated in Fig. 4. Table 6 shows the fault current values seen in each P/B relay. In this optimization problem, 48 variables (TDS-TDS^{24} and PCS-PCS^{24}) existed. The DOCRs coordination problem was solved using the proposed CO technique. Tables 7 and 8 provide optimized TDS, PCS, and OF values. All primary relays' OTs fell within the permissible range of [0.10-1.10 s]. The optimal TDS, PCS, and OF values obtained using the CO approach were compared with results using other proposed techniques in this work. The relevant CTI values are shown in Table 9. The results indicated that by utilizing the proposed CO technique compared to the other proposed optimization techniques in this paper, the total OT of primary DOCRs was decreased. Table 8 illustrates the absence of miscoordination in the optimal results. Additionally, the CO algorithm enhanced the CTI due to the reduction in the sum of CTI values compared with other techniques.



(a) Schematic Diagram.



(b) Simulink Model

Fig. 3 Test System 2.

Table 6 Fault Currents Value for Test System 2 [33].

Fault location	Relay P	Relay B	I_f seen by the primary relay (A)	I_f caught by the backup relay (A)	Fault location	Relay P	Relay B	I_f seen by the primary relay (A)	I_f seen by the backup relay (A)
A	1	15	24,779	9,150	G	13	11	16,087	3,088
	1	17	24,779	15,632		13	21	16,087	13,000
	2	4	8,327	8,327		14	16	18,213	6,285
B	3	1	16,390	16,930		14	19	18,213	11,934
	4	6	14,671	14,671	H	15	13	18,218	6,285
C	5	3	9,454	9,454		15	19	18,218	11,935
	6	8	23,280	4,777		16	2	16,087	3,088
	6	23	23,280	18,507		16	17	16,087	13,000
D	7	5	23,280	4,777	I	18	2	8,161	2,426
	7	23	23,280	18,507		18	15	8,161	5,736
	8	10	9,454	9,454	J	20	13	9,286	4,644
E	9	7	15,304	15,304		20	16	9,286	4,644
	10	12	16,490	16,490	K	22	11	8,161	2,426
F	11	9	8,326	8,327		22	14	8,161	5,736
	12	14	24,779	9,150	L	24	5	6,149	3,075
	12	21	24,779	15,631		24	8	6,149	3,075

Table 7 TDS for Test System 2.

R	MFA [23] TDS	FA-GA [23] TDS	WOA [12] TDS	ChOA TDS	OOA TDS	COA TDS	SOA TDS	POA TDS	CO TDS	Primary OT
1	0.1000	0.1000	0.2316	0.8290	0.6280	0.5550	0.6560	0.3770	0.1110	0.4790
2	0.1000	0.1000	0.1001	0.5270	0.3170	0.3640	0.4230	0.0920	0.0880	0.3070
3	0.1213	0.1117	0.2377	0.6300	0.5640	0.5910	0.6970	0.1980	0.1970	0.4260
4	0.1000	0.1000	1.2000	0.6220	0.3340	0.4900	0.7030	0.1470	0.1470	0.3950
5	0.1000	0.1000	0.1469	0.5560	0.2770	0.4280	0.6320	0.1390	0.1350	0.4400
6	0.1233	0.1124	0.7059	0.6750	0.3220	0.6080	0.9510	0.2190	0.2180	0.4620
7	0.1000	0.1000	0.1761	0.8640	0.4920	0.7990	0.9000	0.2210	0.2100	0.4840
8	0.1000	0.1000	0.5674	0.4630	0.3880	0.4270	0.7550	0.1380	0.1330	0.4580
9	0.1000	0.1000	1.2000	0.4960	0.5330	0.6750	0.7790	0.1480	0.1420	0.4580
10	0.1000	0.1000	0.2193	0.6280	0.4240	0.5480	0.5690	0.1970	0.1960	0.5040
11	0.1000	0.1000	0.6990	0.3820	0.3340	0.4930	0.6870	0.0920	0.0920	0.4260
12	0.1001	0.1001	0.1368	0.7080	0.5080	0.5300	0.7040	0.2720	0.1620	0.5820
13	0.1000	0.1000	0.1454	0.6010	0.6430	0.4760	0.5790	0.1900	0.1300	0.4770
14	0.1000	0.1000	0.1497	0.7800	0.6550	0.7910	0.7510	0.2380	0.1400	0.5780
15	0.4290	0.1142	0.1632	0.7810	0.6250	0.6960	0.7110	0.2400	0.1410	0.5090
16	0.1001	0.1000	1.1431	0.6400	0.6170	0.5490	0.7270	0.1890	0.1760	0.4660
17	0.3754	0.1114	0.2636	0.9080	0.8840	0.7180	0.8160	0.3970	0.3960	0.0000
18	0.1000	0.1000	0.1488	0.1930	0.4920	0.6970	0.0100	0.0990	0.0110	0.1200
19	0.1301	0.1001	0.1225	0.7410	0.9890	0.6560	0.8450	0.2870	0.1860	0.0000
20	0.1001	0.1001	0.1866	0.3220	0.5370	0.1910	0.0410	0.0950	0.0420	0.0940
21	0.1161	0.1001	0.5148	0.8210	0.8340	0.6360	0.7990	0.4660	0.2560	0.0000
22	0.1000	0.1000	0.1765	0.2180	0.3150	0.7150	0.5850	0.1090	0.0220	0.1170
23	0.1000	0.1000	1.2000	0.8760	0.8340	0.8000	0.9370	0.4260	0.4210	0.0000
24	0.1000	0.1000	0.1303	0.1940	0.5070	0.1820	0.0160	0.0820	0.0150	0.1640
OF	10.2370	7.0311	8.3849	10.8290	8.6270	8.5540	10.6550	9.5760	6.2160	

Table 8 PCS for Test System 2.

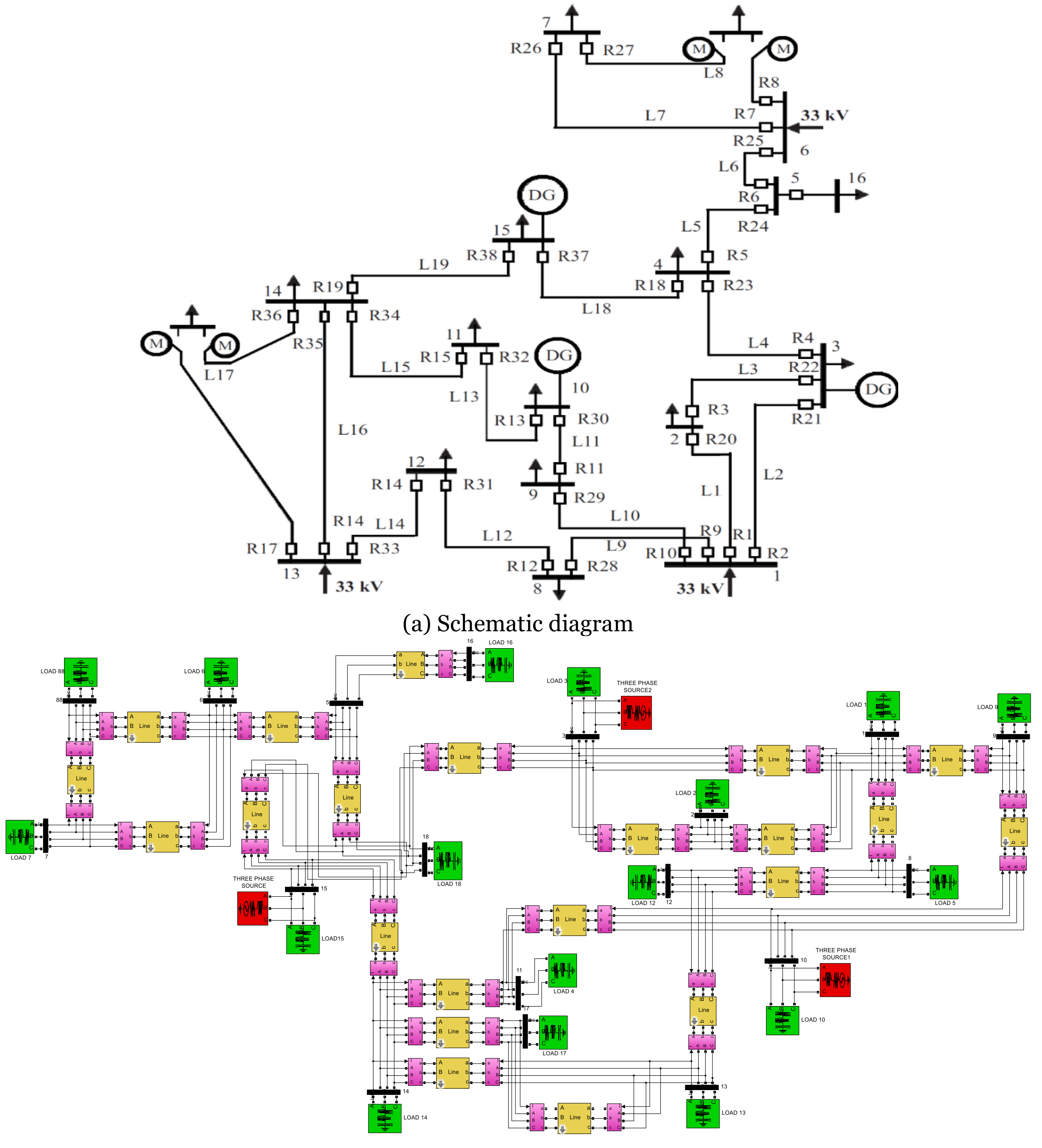
R	MFA [23] PCS	FA-GA [23] PCS	WOA [12] PCS	ChOA PCS	OOA PCS	COA PCS	SOA PCS	POA PCS	CO PCS
1	1.4806	0.7491	2.4466	1.1390	2.3560	2.0040	1.9630	2.5000	0.3110
2	0.5422	0.5001	1.5014	0.6730	1.6430	1.9110	1.9770	2.5000	0.0570
3	0.5828	0.5569	2.4650	1.2420	0.7540	1.0220	0.7180	2.5000	0.2020
4	0.8656	0.6196	2.5000	1.2730	1.4060	1.4580	1.9390	2.5000	0.2340
5	0.7031	0.5065	2.2553	1.0800	1.6900	2.1840	0.6090	2.5000	0.1720
6	0.5673	0.5551	2.5000	1.9470	1.9800	2.2100	1.3410	2.5000	0.2140
7	0.8748	0.6155	2.4542	0.6860	2.0470	1.3890	0.5640	2.5000	0.1100
8	0.5882	0.5001	2.4224	1.4190	1.0780	1.4550	0.8330	2.5000	0.1230
9	0.8313	0.6576	2.5000	1.3170	1.3620	1.9200	0.5730	2.5000	0.2430
10	1.0481	0.6409	2.3922	1.4680	1.5250	0.8320	2.2690	2.5000	0.2090
11	0.9184	0.5536	1.8076	1.1790	2.3990	2.0850	0.5530	2.5000	0.2100
12	0.6562	0.5000	1.8399	1.5820	2.0950	2.4590	1.8040	2.5000	0.2520
13	1.5036	0.5196	2.1276	1.4540	1.3270	1.0270	2.1640	2.5000	0.1610
14	1.9258	0.6039	2.5000	0.7520	2.2100	1.0050	0.8120	2.5000	0.1440
15	0.5043	0.5001	2.0901	0.9690	1.3790	0.7570	1.0780	2.5000	0.2050
16	1.3280	0.5085	2.3815	1.5330	1.7560	1.2620	0.5010	2.5000	0.1170
17	0.5009	0.5003	1.6991	1.6380	1.8710	1.5120	2.2520	1.2200	0.9650
18	0.6570	0.5003	2.2135	1.7010	1.4770	0.8550	2.1420	0.9000	0.0550
19	1.2198	0.6285	1.8376	1.6620	1.8580	1.8470	1.1610	2.1340	0.8820
20	0.6508	0.5001	2.4963	1.2050	1.4130	0.8670	1.9330	0.8020	0.0430
21	1.2047	0.7633	1.5402	1.8400	2.2350	2.3700	1.7970	0.6770	0.2760
22	0.9303	0.5001	2.5000	0.6890	2.0450	1.3110	0.5200	0.6540	0.0320
23	1.1971	0.6355	2.5000	1.3620	1.5920	1.6230	1.6720	0.6690	0.4500
24	0.9272	0.5003	1.9311	0.8650	0.9650	2.1680	0.5010	1.5510	0.0450

Table 9 CTI for Test System 2.

P/Relay	B/Relay	ChOA	OOA	COA	SOA	POA	CO
1	15	0.4778	0.3056	0.2002	0.2000	0.4583	0.1999
1	17	0.3069	0.7309	0.2012	0.6650	1.8102	0.2001
2	4	0.2005	0.1601	0.2001	0.2000	0.2010	0.1525
3	1	0.3076	0.3356	0.2000	0.6287	0.2008	0.2000
4	6	0.4475	0.2406	0.2000	0.2000	0.2150	0.1779
5	3	0.2014	0.3205	0.2020	0.2020	0.2041	0.2000
6	8	0.3754	0.2323	0.2000	0.2000	0.2000	0.1815
6	23	0.2263	1.0338	0.4664	0.9803	1.3197	0.2045
7	5	0.2004	0.4969	0.2003	0.2000	0.2000	0.1517
7	23	0.3949	0.2308	0.4229	0.7306	1.3292	0.2003
8	10	0.5043	0.2935	0.2039	0.2000	0.6783	0.1803
9	7	0.3320	0.2620	0.1999	0.2000	0.2009	0.1974
10	12	0.2453	0.2089	0.2003	0.2000	0.3728	0.1768
11	9	0.2000	0.3542	0.2115	0.2000	0.2009	0.1244
12	14	0.3599	0.1783	0.2005	0.2000	0.2000	0.1288
12	21	0.6624	1.3223	0.2171	0.7667	0.2461	0.2000
13	11	0.2656	0.5667	0.2001	0.2000	0.2257	0.2000
13	21	0.8208	0.8036	0.3978	0.5642	0.8480	0.3545
14	16	0.4633	0.2000	0.2000	0.2000	0.5419	0.1719
14	19	0.6333	1.4151	1.0685	0.2070	0.4440	0.1591
15	13	0.8794	0.5186	0.2000	0.2000	0.2000	0.2000
15	19	0.2038	0.6842	1.0500	0.2001	0.7406	0.1635
16	2	1.0321	0.3180	0.2000	0.2000	0.2188	0.1680
16	17	1.4320	1.8737	0.4355	0.3654	1.4960	0.2770
18	2	2.5095	0.8607	0.7304	0.7298	1.5152	0.5436
18	15	1.4436	2.0167	1.0257	1.3958	1.1422	0.8555
20	13	2.0231	2.2303	0.9056	1.5029	1.2936	0.7970
20	16	1.5031	1.0217	0.8910	1.0451	1.9568	0.7884
22	11	1.4928	1.9926	0.7605	0.7384	0.6851	0.5444
22	14	1.5531	0.9075	0.9813	0.8457	1.3407	0.5330
24	5	1.5510	2.4886	0.9139	0.7960	1.3972	0.6020
24	8	1.1287	0.9843	0.8365	1.2887	1.5292	0.7896
Sum of CTI (s)		16.8341	14.7813	15.7529	14.2218	15.0120	11.2215

4.3. Test System 3

The IEEE 30-bus system (see Fig. 4) with 38 DOCRs was considered the benchmark 3 to evaluate the effectiveness of the suggested techniques in resolving a more extensive power system. Table 10 provides the values for the short-circuit current for faults that occurred near the end. TDS ranges were [0.1 - 1.1], while PCS ranges were [1.5 – 6]. Each relay's CT ratio was assumed to be (1,000/5). The CTI_{min} was set to 0.3 seconds. Tables 11 and 12 display results from the proposed approaches. There was no miscoordination in the CTI estimated from the optimum values of TDS and PCS, as shown in Table 13. As indicated, the results of the proposed CO approach were superior to those of other methods, demonstrating that the suggested technique can be successfully applied to solve the DOCR coordination problem for large-scale power systems. Figures 5-7 illustrate the comparative convergence of all proposed algorithms for test systems 1,2 and 3, respectively. These Figures show how the proposed CO algorithm discovered the global optima for exploration and exploitation during the initial stages of the iterative procedure and for local search during the succeeding iterations for all cases. The proposed CO algorithm had the best performance versus other proposed optimization techniques. The CO algorithm had superior features that advance different proposed strategies by having fast convergence, lower computation time, and reaching optimal solutions without miscoordination, demonstrating that the problem of DOCR coordination for bulky power systems can be solved effectively using the proposed algorithm. Table 14 illustrates a statistical evaluation of the results based on all proposed approaches. The statistical analysis was based on comparing the results' minimum, maximum, and standard deviation over ten runs. The problem was solved using various beginning options, including middle values between the lower and upper limits of control variables, lower limits of control variables, and upper limits of control variables. It provides an acceptable solution in some scenarios, however, worse than the CO technique. Furthermore, some optimization methods terminated for test system 3 in situations with upper and middle initial control variable choices without attaining a feasible solution. It is evident that the proposed CO algorithm offered superior and more stable solutions for all three test systems than the optimization techniques used in this work. From the simulation results in Table 14, it is clear that CO showed the best and most advanced computational performance with the lowest cost and standard deviation, proving that Co results were more dependable and less diverse. On the other hand, a high standard deviation indicated a larger range of values. In an optimization setting, a reduced standard deviation indicated values closer to the mean or probable value, which is preferred since it indicates consistent solution quality near the ideal.



(a) Schematic diagram

(b) Simulink model

Fig. 4 Test System 3.

Table 10 Fault Currents Value for Test System 3 [34].

P/ relay	B/ relay	$I_{f\ primary}$ (A)	$I_{f\ primary}$ (A)	P/relay	B/relay	$I_{f\ backup}$ (A)	$I_{f\ backup}$ (A)
3	1	4,086.7	4,086.7	9	20	7,212.6	1,103.5
4	2	5,411.2	2,138.8	10	20	7,339.3	1,095.8
22	2	4,333.0	2,147.0	1	21	7,665.3	698.8
4	3	5,411.2	3,272.5	9	21	7,212.6	721.2
21	3	5,411.8	3,243.6	10	21	7,339.3	716.1
5	4	4,960.8	3,001.3	20	22	3,481.5	3,481.5
18	4	4,719.4	3,002.1	21	23	5,411.8	2,193.5
6	5	2,416.0	2,416.0	22	23	4,333.0	2,204.6
7	6	5,669.0	1,790.9	18	24	4,719.4	1,717.7
8	6	5,607.7	1,774.8	23	24	3,689.7	1,724.2
27	7	1,472.3	1,472.3	24	25	2,695.0	2,695.0
26	8	1,026.8	1,026.8	1	28	7,665.3	1,552.0
12	9	5,034.9	5,034.9	2	28	7,985.7	1,545.8
11	10	3,457.1	3,457.1	10	28	7,339.3	1,538.0
13	11	3,727.3	2,875.0	1	29	7,665.3	1,380.6
14	12	2,906.5	2,906.5	2	29	7,985.7	1,375.2
15	13	2,660.5	2,660.5	9	29	7,212.6	1,379.0
16	14	6,185.6	1,668.1	29	30	2,518.9	2,518.9
17	14	7,492.9	1,641.1	28	31	2,036.8	2,036.8

19	15	5,445.2	1,527.3	30	32	2,998.8	2,149.0
35	15	4,222.0	1,533.2	31	33	3,263.6	3,263.6
36	15	6,420.2	1,509.7	32	34	2,930.4	2,930.4
19	16	5,445.2	3,128.3	17	35	7,492.9	1,885.4
34	16	5,796.6	3,123.9	33	35	6,456.2	1,954.5
36	16	6,420.2	3,052.4	16	36	6,185.6	490.9
19	17	5,445.2	801.3	33	36	6,456.2	500.6
34	17	5,796.6	800.1	5	37	4,960.8	1,961.0
35	17	4,222.0	794.0	23	37	3,689.7	1,968.5
38	18	3,133.2	2,292.2	34	38	5,796.6	1,886.8
37	19	3,788.9	2,940.9	35	38	4,222.0	1,896.7
2	20	7,985.7	1,053.9	36	38	6,420.2	1,867.7

Table 11 TDS for Test System 3.

Relay	FA-LP [5] TDS	AVOA [13] TDS	WOA [12] TDS	HHO-SQP [35] TDS	ChOA TDS	OOA TDS	COA TDS	SOA TDS	POA TDS	CO TDS	$OT_{Prim.}$
1	0.4058	1.0900	0.1131	0.2643	0.9330	0.8940	0.2730	0.5060	0.5800	0.1000	3.7740
2	0.2365	1.0600	0.1000	0.1710	0.8600	0.6050	0.2260	0.8010	0.7720	0.1000	1.8270
3	0.1000	1.0900	0.1007	0.1844	0.7080	0.6280	0.2320	0.4440	1.0150	0.1000	5.3290
4	0.1834	1.0500	0.1007	0.2288	0.9420	0.9340	0.1580	0.9610	0.7050	0.1000	3.4980
5	0.1037	1.0900	0.1000	0.1487	0.6580	0.9090	0.1950	0.3900	0.5820	0.1000	2.5860
6	0.1000	1.0700	0.9236	0.1005	0.4230	0.6670	0.1380	0.7250	0.3140	0.1000	2.4520
7	0.1000	1.0900	0.1000	0.1000	0.9100	0.3110	0.1480	1.0960	0.8580	0.1090	2.0540
8	0.1000	1.0500	0.1000	0.1000	0.5390	0.5750	0.1000	0.9530	1.1000	0.1000	2.7880
9	0.3483	1.0800	0.1001	0.2624	0.9200	0.4930	0.2810	1.0650	1.0550	0.1000	1.4320
10	0.2430	1.0900	0.1002	0.2754	0.9860	0.6610	0.2630	1.1000	0.5380	0.1000	1.1700
11	0.1171	1.0900	0.1076	0.2162	0.7430	0.6470	0.2550	1.0840	0.6940	0.1000	1.2240
12	0.1340	1.0900	0.1000	0.1985	0.9280	0.5660	0.1600	0.7720	0.4910	0.1000	1.2620
13	0.1227	1.0900	0.1074	0.1805	0.5410	0.8520	0.1990	0.7050	0.9340	0.1040	1.0310
14	0.1000	1.1000	1.0933	0.1572	0.2090	0.4590	0.1770	0.7030	0.5000	0.1000	1.3550
15	0.1000	1.0900	0.6461	0.2060	0.4580	0.6300	0.1740	0.9410	0.3110	0.1000	1.0730
16	0.2009	1.1000	0.8541	0.4428	0.5040	0.2740	0.2050	0.2730	0.1000	0.1000	1.7420
17	0.3658	1.1000	0.2737	0.1438	0.6160	0.7240	0.1160	0.3840	0.8940	0.1000	0.3870
18	0.1000	0.9600	0.6984	0.1749	0.1870	0.6840	0.2110	0.5270	1.0030	0.1000	3.0430
19	0.2365	1.0600	0.1046	0.1978	0.8280	0.4300	0.2200	0.4530	0.2640	0.1000	1.3660
20	0.1001	0.9000	0.2328	0.1880	0.5250	0.4950	0.1050	0.1860	0.1700	0.1000	0.9970
21	0.1000	0.9300	0.1672	0.2050	0.5680	0.3920	0.1280	0.1120	0.7980	0.1000	0.8370
22	0.1202	0.9500	0.1118	0.2128	0.7630	0.6380	0.1760	1.0780	0.9650	0.1000	1.1920
23	0.1039	1.0700	0.1003	0.1864	0.7430	0.6110	0.1700	0.8130	0.4630	0.1000	1.2070
24	0.1000	1.0900	0.1000	0.1465	0.5840	0.6080	0.1450	0.7210	0.3050	0.3940	7.8490
25	0.1066	1.0900	0.1013	0.2104	0.6560	0.5240	0.2440	0.4300	0.4450	0.6140	0.0000
26	0.1000	0.7600	0.1757	0.1046	0.6370	0.3780	0.1000	1.1000	0.1760	0.1000	3.1870
27	0.1005	0.7900	0.1037	0.1000	0.7400	0.3730	0.1130	1.1000	0.1010	0.1560	0.4440
28	0.1000	1.1000	0.2170	0.3286	0.9520	0.5670	0.1440	0.5140	0.5050	0.1000	3.7290
29	0.1000	1.1000	0.1990	0.1301	0.1610	0.3570	0.1580	0.1110	0.1080	0.1000	2.1440
30	0.1000	1.0900	0.2856	0.1406	0.6420	0.5610	0.2430	0.3590	0.1730	0.1000	4.4580
31	0.1125	1.0800	0.3598	0.1906	0.8430	0.5300	0.1790	0.2910	0.1320	0.1000	2.8830
32	0.1526	0.8800	0.1049	0.1627	0.7390	0.3020	0.1950	0.4400	0.1000	0.1000	3.1110
33	0.1023	1.0400	0.1522	0.2426	0.7690	0.4230	0.2110	0.1020	0.1110	0.1000	2.1920
34	0.1025	1.1000	0.1000	0.2332	0.8800	0.3800	0.1750	0.2570	0.2840	0.1000	1.9690
35	0.1000	1.0800	0.2242	0.2336	0.4810	0.9130	0.1600	0.2210	0.8510	0.1000	1.3660
36	0.1000	1.1000	0.1271	0.2080	0.9550	0.1000	0.1030	0.1000	0.1000	0.1000	0.2580
37	0.1000	0.9300	0.1727	0.1951	0.7470	0.5990	0.1390	0.5920	0.2050	0.1000	1.9510
38	0.1000	1.0300	0.2007	0.1594	0.3080	0.8960	0.1510	1.0420	0.5060	0.1000	1.5800
OF	11.3692S	46.5700	15.7139	20.6085	33.7740	51.4510	17.3320	41.9960	20.3050	9.9850	

Table 12 PCS for Test System 3.

R	FA-LP [5] PCS	AVOA [13] PCS	WOA [12] PCS	HHO-SQP [35] PCS	ChOA PCS	OOA PCS	COA PCS	SOA PCS	POA PCS	CO PCS
1	1.9658	2.0300	1.6958	2.5000	2.5100	4.6170	3.8160	5.9170	5.0960	1.5000
2	2.5000	2.0700	1.5000	2.2414	4.9010	3.6200	1.9960	2.4950	3.0440	1.5000
3	2.5000	1.7400	1.5109	2.5000	5.3130	5.0300	2.9300	5.9610	1.5810	4.6180
4	2.5000	1.8500	1.5111	2.4533	2.4940	4.4480	4.7930	1.5420	2.9410	4.8430
5	2.5000	1.7800	1.5000	2.5000	4.6520	3.8360	2.5600	5.8020	3.7770	5.0290
6	1.5645	1.5000	2.4761	2.2634	4.2870	3.2180	2.2510	2.4890	5.6870	3.3780
7	1.5582	1.7800	1.5005	1.7095	3.3770	5.2280	2.1360	1.6510	1.5540	4.3810
8	1.9986	1.8100	1.5000	1.3688	3.1170	3.0280	2.2980	4.0200	2.4760	6.0000
9	2.5000	2.0000	1.5029	2.5000	3.7330	4.4970	3.3350	4.5330	2.2030	1.5000
10	2.5000	1.9400	1.5042	2.5000	4.4340	3.8020	4.1050	1.6000	5.5570	1.5000
11	1.9658	2.2200	1.6149	2.4849	3.5240	3.8570	2.7770	1.5390	3.5800	4.1170
12	2.5000	1.9200	1.5000	2.5000	3.1890	3.1810	4.6800	5.9800	2.0140	3.4280
13	2.5000	2.1500	1.6118	2.5000	3.0920	3.6500	3.1550	4.0260	2.1770	6.0000
14	1.7783	1.9100	2.4849	2.3034	4.6180	3.9010	2.3980	5.8840	1.6220	2.4820
15	1.8956	1.8900	2.3447	1.2171	3.3350	2.7560	2.1240	2.0440	3.6040	6.0000
16	2.5000	1.8800	1.9412	0.5064	4.9360	3.6110	3.9220	1.5120	6.0000	2.1300
17	1.9864	2.0500	1.7453	1.0709	1.9980	3.0100	1.8200	1.9400	1.6160	6.0000

18	2.5000	1.8100	2.1623	2.5000	5.5450	3.9830	2.6050	4.3360	1.6430	4.3990
19	2.5000	1.8000	1.5824	2.5000	2.9300	5.1310	2.6100	1.6620	3.4410	1.5000
20	2.5000	1.7300	2.4762	1.7467	3.9940	3.2900	2.8560	4.9560	3.7220	6.0000
21	1.6783	1.6900	2.3334	0.9541	2.5000	2.6960	1.6160	2.9950	3.0040	6.0000
22	2.5000	1.7800	1.6782	2.5000	5.1490	4.5930	3.0960	1.5300	4.1200	5.4890
23	2.5000	1.7700	1.5000	2.5000	4.1180	2.5870	3.0800	1.5000	5.5700	4.4280
24	2.3326	1.6900	1.5000	2.5000	4.0600	4.3280	3.0070	1.9370	5.9980	3.3110
25	1.8764	2.0200	1.5205	2.5000	3.3790	5.2840	2.3750	5.1560	5.9970	2.0570
26	1.9983	1.5200	2.3145	0.5000	5.2740	3.0910	1.5000	1.5080	1.5330	1.5000
27	1.6738	1.6000	1.5555	0.5000	3.3860	3.6600	1.6700	1.5180	2.2160	2.8250
28	1.7782	1.6300	2.3228	0.7392	2.5530	4.2620	3.1630	1.5160	1.5520	1.7200
29	2.5000	1.8100	2.1887	2.0633	4.4770	3.3710	2.5690	5.9970	5.2910	1.6140
30	2.5000	2.0500	2.5000	2.5000	4.4070	2.0130	2.3010	2.2110	4.1770	2.5200
31	1.9852	2.0200	2.0241	2.5000	4.3420	4.4390	3.4710	2.5550	6.0000	2.3860
32	1.7878	1.9100	1.5747	2.5000	5.2610	4.8230	3.4630	1.5050	5.8020	2.1870
33	1.6985	2.0400	2.1039	2.5000	4.9750	2.8740	4.3110	3.3400	2.9370	1.5000
34	2.5000	1.7000	1.5006	2.5000	3.6390	4.0830	5.4940	3.9800	1.5040	1.5000
35	2.2205	1.8400	2.4661	1.4544	4.4570	4.1390	3.2920	2.5100	1.5390	1.5000
36	1.8965	1.8200	1.9075	0.5000	1.8670	5.5580	1.5000	5.9890	6.0000	6.0000
37	2.3326	1.8400	2.4772	1.8878	4.3460	4.3030	3.5790	1.5000	5.9680	3.5540
38	2.5000	1.9800	1.7111	2.5000	3.7550	3.6210	3.3920	1.5000	5.2100	3.4530

Table 13 CTI for Test System 3.

P/Relay	B/Relay	ChOA	OOA	COA	SOA	POA	CO
3	1	0.5808	0.1549	1.0540	0.2026	0.3000	0.1319
4	2	4.9518	2.8541	0.3121	0.0505	0.3002	0.2135
22	2	3.9504	1.8032	1.0218	1.1541	1.3038	1.0110
4	3	1.6542	2.0547	0.7276	0.3465	0.3000	0.1644
21	3	2.7594	0.5790	2.5483	0.0925	0.6211	0.0261
5	4	0.9019	0.6090	1.9666	0.1803	0.3685	0.0105
18	4	2.7178	1.1737	2.6646	2.2021	1.3001	0.7469
6	5	1.9552	1.4522	1.9999	0.2493	0.3002	0.2295
7	6	1.0606	2.3062	1.2474	0.3101	0.3001	0.2902
8	6	2.3596	1.8092	2.7845	0.2708	0.4213	0.1722
27	7	1.4902	2.1452	2.6258	0.3298	0.3001	0.2545
26	8	1.8520	2.4905	2.4022	1.0597	0.9016	0.7106
12	9	0.2294	0.5028	0.3931	0.6029	0.3005	0.0661
11	10	1.7828	0.1551	0.2383	0.2015	0.3005	0.0963
13	11	1.5780	0.2197	0.2024	0.9810	0.3000	0.1510
14	12	2.9582	0.2992	0.1620	0.3886	0.3001	0.1375
15	13	0.2722	0.3101	1.7951	0.4333	0.3002	0.3000
16	14	0.5690	2.9785	1.3166	0.3158	0.3000	0.2427
17	14	1.0985	2.0207	2.3241	0.2032	0.7331	0.1682
19	15	1.2918	3.2985	2.5078	2.6608	0.3002	0.1284
35	15	1.6881	2.0276	0.4055	2.5920	0.3455	0.2041
36	15	1.6054	1.5770	3.9381	2.6315	0.7228	0.5648
19	16	0.4805	0.4145	0.4828	0.4096	0.3822	0.3025
34	16	0.1195	1.0640	0.0979	0.1149	0.3001	0.0873
36	16	0.8058	0.6429	0.9202	0.5619	0.8148	0.3983
19	17	2.9161	2.1669	1.7244	1.9749	0.6326	0.4666
34	17	1.2582	2.5508	1.4337	1.9634	0.2999	0.1998
35	17	4.1063	2.4874	1.3966	1.9597	0.4413	0.4150
38	18	0.3044	1.0541	0.2652	0.2681	0.3002	0.1248
37	19	0.4354	0.6070	0.2388	0.1116	0.3002	0.1715
2	20	1.4091	1.6648	1.6019	1.6053	0.6841	0.1795
9	20	2.5571	2.0148	2.0457	2.5700	0.3058	0.2629
10	20	1.3877	1.2143	1.7662	2.9251	0.3034	0.0441
1	21	1.5133	2.3311	1.6604	1.5107	0.3485	0.1982
9	21	1.0456	1.2039	1.7848	1.5950	0.3046	0.1796
10	21	2.8388	1.8694	2.6492	1.5749	0.3002	0.2840
20	22	1.8744	1.2835	1.2584	0.7507	0.3001	0.0065
21	23	3.6257	2.6944	1.7525	0.5070	0.6142	0.4576
22	23	1.5646	3.1366	0.0732	0.2576	0.3000	0.0265
18	24	1.5233	1.1027	2.5225	2.4550	0.3021	0.1967
23	24	1.9714	1.0420	2.0008	2.3698	0.3014	0.1188
24	25	0.0923	2.0264	0.1789	0.3082	0.3002	0.1502
1	28	2.6008	2.1438	1.6901	0.2485	0.3030	0.0168
2	28	1.1431	1.8640	1.9083	0.2525	0.6042	0.2074
10	28	2.7844	2.7616	1.6922	0.2484	0.3019	0.2017
1	29	0.2598	1.3656	0.5648	0.2657	0.3000	0.1700
2	29	0.1958	1.0827	1.7576	0.2697	0.6007	0.1239
9	29	0.1775	2.7516	1.8423	0.2620	0.3032	0.0580
29	30	1.1585	1.8467	0.2334	0.0943	0.3001	0.3060
28	31	1.1108	1.5412	0.5893	0.4887	0.3002	0.3001
30	32	2.5688	1.1250	0.7035	0.4472	0.3003	0.2500
31	33	0.5811	1.0675	1.1372	1.0707	0.3002	0.2385
32	34	0.6388	0.9686	0.1692	1.0608	0.3031	0.0381
17	35	1.0284	1.5224	1.7408	1.0013	0.7947	0.2735

33	35	1.4249	2.9891	1.1810	0.1454	0.3000	0.1175
16	36	2.4889	2.3590	1.7381	1.0448	0.7692	0.4066
33	36	1.9191	1.1483	2.0787	1.0288	0.6740	0.1158
5	37	3.6697	1.6790	1.7072	0.2511	0.3694	0.1179
23	37	2.9316	0.7434	2.8953	0.1967	0.3003	0.0491
34	38	0.5917	1.4624	2.1587	0.4601	0.3002	0.0071
35	38	0.1740	1.5479	2.5935	0.4281	0.4262	0.1714
36	38	0.0579	1.0538	1.1661	0.2862	0.8076	0.1066
Sum of CTI (s)		53.628	51.321	47.119	41.776	50.292	25.412

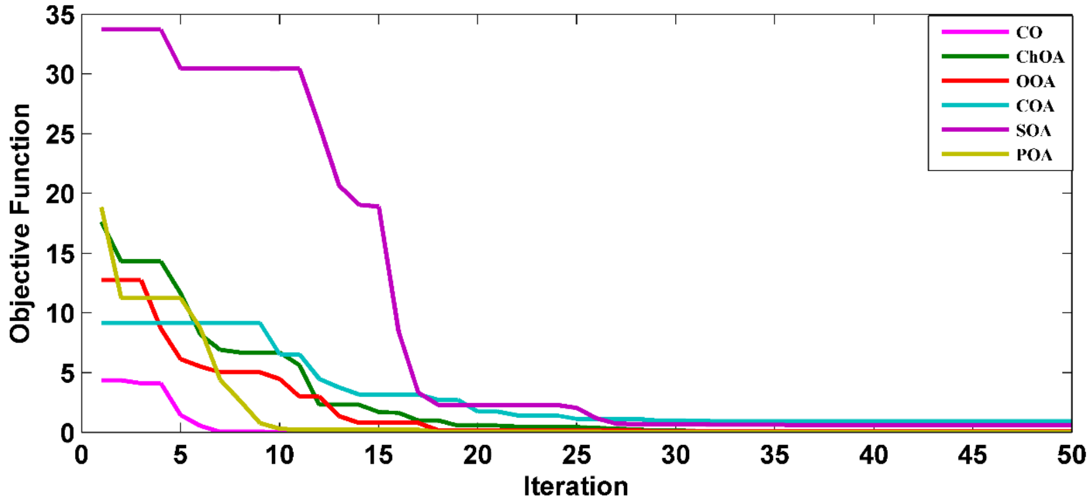


Fig. 5 Convergence Curves for Test System 1.

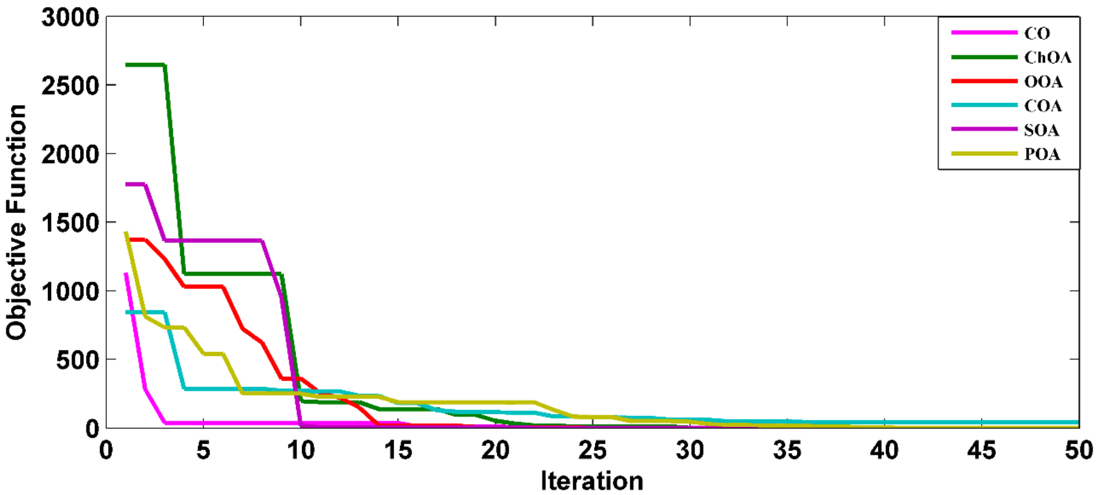


Fig. 6 Convergence Curves for Test System 2.

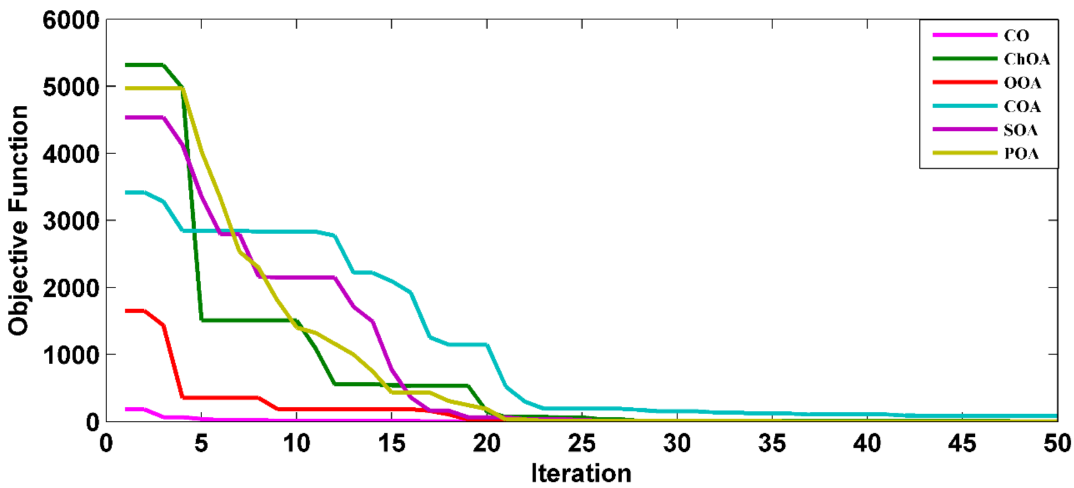


Fig. 7 Convergence Curves for Test System 3.

Table 14 Comparison of Statistical Results for (OF).

Technique		Test System 1	Test System 2	Test System 3
ChOA	Min.	1.4841	10.829	33.774
	Max.	4.995	17.885	65.874
	Std. dev.	4.653	4.874	5.441
OOA	Min.	1.3704	8.627	51.451
	Max.	4.973	16.879	67.453
	Std. dev.	1.983	4.763	5.934
COA	Min.	1.2735	8.554	17.332
	Max.	4.879	18.452	58.874
	Std. dev.	3.325	3.576	5.764
SOA	Min.	1.1798	10.655	41.966
	Max.	4.999	15.443	53.764
	Std. dev.	2.994	3.884	6.112
POA	Min.	1.1963	9.576	20.305
	Max.	4.989	15.875	59.654
	Std. dev.	3.574	6.453	5.876
CO	Min.	0.6703	6.216	9.985
	Max.	4.693	7.874	28.659
	Std. dev.	0.066	0.105	0.213

5.CONCLUSION

Each relay's TDS and PCS are considered decision variables in the coordination between DOCRs, which is a nonlinear and severely constrained optimization problem. The primary objective is to reduce the total amount of OTs across all primary relays, which must be in operation to fix the issues with their zones that match. CO optimization technique has been suggested and effectively used in this paper to address the coordination issue with DOCRs. Three different test systems were used for testing and investigating the proposed technique. The proposed algorithm's results were compared with several recently developed competitors. From the obtained results for the three-test systems, CO showed the best results advanced to that obtained from other used techniques. For all test systems, CO achieved the lowest OTs, enhancing the CTI, and fastest convergence rate. The best total relay operating times for test systems 1, 2, and 3 were 0.6703 s, 6.216 s, and 9.985 s, respectively. While the lowest OTs standard deviation were 0.066, 0.105, and 0.213 respectively. All obtained OTs were within their acceptable bounds, demonstrating no miscoordination pairings when the DOCRs were operating. A thorough statistical analysis confirmed the proposed technique's reliability, stability, and consistency. The suggested method provided reliable, superior responses quickly and efficiently. It also had a high convergence, which benefits adaptive coordination by enhancing grid control, communication, and monitoring. The CO algorithm offered a superior, robust solution based on the simulation results. Furthermore, the results attained using the CO algorithm were either better or comparable to those obtained using other techniques in this paper. The proposed CO algorithm was proper for finding the global optimal solution in DOCRs coordination problems.

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NOMENCLATURE

CTI_{min}	Time interval for min. Coordination
I_{ik}	Fault current seen by the ith relay for a fault located at k
m	Number of relays
m_p	Number of P/B relays
p	P/B relay range [1- m_p]
PCS_i	Pickup current of the ith relay
PCS_i^{max}	Upper bound PCS of the ith relay
PCS_i^{min}	Lower bound of PCS of the ith relay
$\overset{-1}{r}_{i,j}$	Randomized parameter for the ith cheetah
$\overset{\vee}{r}_{i,j}$	Turning factor related to the ith cheetah
t and T	Current length of hunting time
T	Maximum length of hunting time
T_{ik}^{max}	Upper bound of operation times of the ith relay for a fault location at point k
T_{ik}^{min}	Lower bound of operation times of the ith relay for a fault location at point k,
TDS_i	Time dial settings of the ith relay
TDS_i^{max}	Upper bound of TDS of the ith relay
TDS_i^{min}	Lower bound of TDS of the ith relay
$X_{B,j}^{t}$	Prey's current position
$X_{i,j}^{t}$	Current position of the ith cheetah
$X_{i,j}^{t+1}$	Next position of the ith cheetah
ΔT_{mbp}	Difference in operation time with CTI between relay pair
Greek symbols	
α and n	Constants related to the IEC standardized
α_1 and α_2	Control weighting parameters of modified OF
$\alpha_{i,j}^{t}$	Step length for the ith cheetah
β	Miscoordination parameter
$\beta_{i,j}^{t}$	Interaction factor related to the ith cheetah

REFERENCES

[1] Kida AA, Rivas AEL, Gallego LA. **An Improved Simulated Annealing–Linear Programming Hybrid Algorithm Applied to the Optimal**

Coordination of Directional Overcurrent Relays. *Electric Power Systems Research* 2020; **181**: 106197.

[2] Ibrahim MH, Jasim AH. **Voltage Collapse Prediction of IEEE 30-Bus System.** *Tikrit Journal of Engineering Sciences* 2021; **28**(1): 98-112.

[3] Mohammed RK, Alhamdany UA, Çetinkaya N. **A Load Flow Analysis Method for Kufa Cement Plant.** *Tikrit Journal of Engineering Sciences* 2020; **27**(3): 1-9.

[4] Hussein AA. **Load Frequency Control for Two-Area Multi-Source Interconnected Power System Using Intelligent Controllers.** *Tikrit Journal of Engineering Sciences* 2018; **25**(1): 78-86.

[5] Ramli SP, Mokhlis H, Wong WR, Muhammad MA, Mansor NN. **Optimal Coordination of Directional Overcurrent Relay Based on Combination of Firefly Algorithm and Linear Programming.** *Ain Shams Engineering Journal* 2022; **13**(6): 101777.

[6] Khaleel II. **Power System Transient Stability Improvement Using Fuzzy Logic.** *Tikrit Journal of Engineering Sciences* 2015; **22**(2): 40-46.

[7] Al-Flaiyeh MA, Aziz NH. **Enhancement Stability of the Power System Using Static Synchronous Compensators Connected in Different Formats.** *Tikrit Journal of Engineering Sciences* 2021; **28**(1): 1-12.

[8] Mohammadzadeh N, Chabanloo RM, Maleki MG. **Optimal Coordination of Directional Overcurrent Relays Considering Two-Level Fault Current Due to the Operation of Remote Side Relay.** *Electric Power Systems Research* 2019; **175**: 105921.

[9] Omidi P, Abazari S, Madani S. **Optimal Coordination of Directional Overcurrent Relays for Microgrids Using Hybrid Interval Linear Programming - Differential Evolution.** *Journal of Operation and Automation in Power Engineering* 2022; **10**(2): 122-133.

[10] Muhammad Y, et al. **Optimal Coordination of Directional Overcurrent Relays Using Hybrid Fractional Computing with Gravitational Search Strategy.** *Energy Reports* 2021; **7**: 7504-7519.

[11] Gokhale SS, Kale VS. **On the Significance of the Plug Setting in Optimal Time Coordination of Directional Overcurrent Relays.** *International Transactions on Electrical Energy Systems* 2018; **28**(11): e2615.

[12] Wadood A, et al. **Nature-Inspired Whale Optimization Algorithm for Optimal Coordination of Directional Overcurrent Relays in Power Systems.** *Energies* 2019; **12**(12): 2297.

[13] Korashy A, Kamel S, Jurado F, Eslami M. **Optimal Coordination of Distance Relays and Non-Standard Characteristics for Directional Overcurrent Relays Using a Modified African Vultures Optimization Algorithm.** *IET Generation, Transmission and Distribution* 2023.

[14] Chawla A, Bhalja BR, Panigrahi BK, Singh M. **Gravitational Search Based Algorithm for Optimal Coordination of Directional Overcurrent Relays Using User Defined Characteristic.** *Electric Power Components and Systems* 2018; **46**(1): 43-55.

[15] Effatnejad R, Aliyari H, Savaghebi M. **Solving Multi-Objective Optimal Power Flow Using Modified GA and PSO Based on Hybrid Algorithm.** *Journal of Operation and Automation in Power Engineering* 2017; **5**(1): 51-60.

[16] Abed WNA-D, Imran OA, Fatah IS. **Automatic Generation Control Based Whale Optimization Algorithm.** *International Journal of Electrical and Computer Engineering* 2019; **9**(6): 4516.

[17] Abed WNA-D, Imran OA, Abdullah AN. **Sensored Speed Control of Brushless DC Motor Based Salp Swarm Algorithm.** *International Journal of Electrical and Computer Engineering* 2022; **12**(5): 4832-4840.

[18] Al-Suhili R, Karim RA. **A Genetic Algorithm Optimization Model for Stability of an Inclined Cutoff with Soil-Embedded Depth.** *Tikrit Journal of Engineering Sciences* 2023; **30**(2): 31-40.

[19] Abed WNA-D. **Solving Probabilistic Optimal Power Flow with Renewable Energy Sources in Distribution Networks Using Fire Hawk Optimizer.** *E-Prime-Advances in Electrical Engineering, Electronics and Energy* 2023; **6**: 100370.

[20] Masereka EB, Kitagawa W, Takeshita T. **Optimal Coordination of Directional Overcurrent Relays Considering a Modified Objective Function Using Genetic Algorithm.** *20th International Conference on Intelligent System Application to Power Systems (ISAP) 2019;* IEEE; 2019: 1-6.

[21] Kamel S, Korashy A, Youssef A-R, Jurado F. **Development and Application of**

an Efficient Optimizer for Optimal Coordination of Directional Overcurrent Relays. *Neural Computing and Applications* 2020; **32**: 8561-8583.

[22] Habib K, et al. **Hybridization of PSO for the Optimal Coordination of Directional Overcurrent Protection Relays.** *Electronics* 2022; **11**(2): 180.

[23] Foqha T, et al. **Optimal Coordination of Directional Overcurrent Relays Using Hybrid Firefly–Genetic Algorithm.** *Energies* 2023; **16**(14):5328.

[24] Rajput VN, Adelnia F, Pandya KS. **Optimal Coordination of Directional Overcurrent Relays Using Improved Mathematical Formulation.** *IET Generation, Transmission and Distribution* 2018; **12**(9): 2086-2094.

[25] Abed W, Imran O, Jbarah A. **Voltage Control of Buck Converter-Based Ant Colony Optimization for Self-Regulating Power Supplies.** *Journal of Engineering and Applied Sciences* 2018; **13**: 4463-4467.

[26] Abed WNA-D, Saleh AH, Hameed AS. **Speed Control of PMDCM Based GA and DS Techniques.** *International Journal of Power Electronics and Drive Systems* 2018; **9**(4): 1467.

[27] Abd Elaziz M, Ghoneimi A, Nabih M, Bakry A, Al-Betar MA. **Contribution of Fluid Substitution and Cheetah Optimizer Algorithm in Predicting Rock-Physics Parameters of Gas-Bearing Reservoirs in the Eastern Mediterranean Sea, Egypt.** *Natural Resources Research* 2023; **32**(5):1987-2005.

[28] Akbari MA, Zare M, Azizipanah-Abarghooee R, Mirjalili S, Deriche M. **The Cheetah Optimizer: A Nature-Inspired Metaheuristic Algorithm for Large-Scale Optimization Problems.** *Scientific Reports* 2022; **12**(1): 10953.

[29] Ghaedi H, Kamel Tabbakh SR, Ghaemi R. **Improving Performance of the Convolutional Neural Networks for Electricity Theft Detection by Using Cheetah Optimization Algorithm.** *Majlesi Journal of Electrical Engineering* 2022; **16**(4): 103-115.

[30] Ghaedi H, Kamel Tabbakh Farizani SR, Gaemi R. **A Novel Meta-Heuristic Framework for Solving Power Theft Detection Problem: Cheetah Optimization Algorithm.** *International Journal of Industrial Electronics Control and Optimization* 2022; **5**(1): 63-76.

[31] Thangaraj R, Pant M, Deep K. **Optimal Coordination of Over-Current Relays Using Modified Differential Evolution Algorithms.** *Engineering Applications of Artificial Intelligence* 2010; **23**(5): 820-829.

[32] Chelliah TR, Thangaraj R, Allamsetty S, Pant M. **Coordination of Directional Overcurrent Relays Using Opposition Based Chaotic Differential Evolution Algorithm.** *International Journal of Electrical Power and Energy Systems* 2014; **55**: 341-350.

[33] Singh M, Panigrahi BK, Abhyankar AR, Das S. **Optimal Coordination of Directional Over-Current Relays Using Informative Differential Evolution Algorithm.** *Journal of Computational Science* 2014; **5**(2): 269-276.

[34] Mohammadi R, Abyaneh HA, Rudsari HM, Fathi SH, Rastegar H. **Overcurrent Relays Coordination Considering the Priority of Constraints.** *IEEE Transactions on Power Delivery* 2011; **26**(3): 1927-1938.

[35] ElSayed SK, Elattar EE. **Hybrid Harris Hawks Optimization with Sequential Quadratic Programming for Optimal Coordination of Directional Overcurrent Relays Incorporating Distributed Generation.** *Alexandria Engineering Journal* 2021; **60**(2): 2421-2433.