Application of Equilibrium Optimizer Algorithm for Solving Linear and non Linear Coordination of Directional Overcurrent Relays

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Abstract. *The safety and reliability of an electrical network depend on the performance of the protections utilized. Therefore, the optimal coordination of the protective devices plays an essential role. In this paper, a new algorithm, Equilibrium Optimizer (EO), which is based on the physical equation of the mass balance, is implemented in the problem of the Optimal Coordination of Directional Overcurrent Relays (DOCRs). Moreover, the proposed method uses Linear Programming (LP), Nonlinear Programming (NLP) and Mixed-Integer Nonlinear Programming (MINLP) in order to optimize the Time Dial Setting (TDS), as well as the Plug Setting (PS), satisfying all possible constraints. Additionally, the performance of EO is evaluated using several benchmarks with different topologies. The results demonstrated the applicability and efficacy of the proposed approach. A comparison with other studies reported in specialized literature is provided to demonstrate the benefits of the proposed approach.*

Keywords

Distributed Generation, Equilibrium Optimizer, Optimal Coordination, Overcurrent Relay.

1. Introduction

The coordination of maximum current relays plays a vital role in the protection of electrical networks. In the interest of having continuity in electrical energy under extreme conditions, electrical engineers have been trying, for decades, to improve the design of the protection by using new techniques. Having a satisfactory protection plan means that the operating time of the directional relays must be optimized [1]. In distribution lines, overcurrent relays are used as primary protection, while in transmission lines, they are used as secondary protection. An effective coordination of these two ensures proper functioning of the healthy part of the network during the occurrence of any faults [2].

When any failure occurs, the network in question will be protected by the primary relays [3] that must work to eliminate the fault and isolate the affected area, otherwise it is the secondary relays that will act after a specified time interval named CTI [2] and [4]. Moreover, to ensure the reliability and safety of the transmission and interconnection of electrical networks, the relays with maximum current must be equipped with directional functionality. The Operating Time (OT) of the maximum current directional relay is determined by two design variables: TDS (Time Dial Setting) and IP (Pickup Current) or PS (Plug Setting) [5].

The optimization of the coordination of relays at maximum current can be modelled according to three formulations. The first one is Linear Programming (LP), where the TDS is the only variable to optimize while keeping the PS value constant, and thus it requires initial PS values. The second is Non-Linear Programming (NLP), where the design variables are TDS and IP, the latter taking continuous values. Finally, there is the third formulation, which is continuous Non-Linear or Mixed-Integer Programming (MINLP), where the variables are TDS and PS to be optimized. The difference between the two formulations is that PS takes continuous values in (NLP), while PS takes discrete values in (MINLP).

A plethora of techniques can be used to solve the problem of optimal coordination of DOCRs. Among these techniques are the meta-heuristic methods, which are bio-inspired by nature. To name a few, Harris Hawks Optimization and Jaya algorithm hybrid with LP, NLP, and MINLP formulations [5]. An algorithm based on the hybridization of Biogeography-Based Optimization with Linear Programming (BBO-LP) is used in [6]. The Water Cycle Algorithm (WCA) is proposed by [7]. The Firefly (FA) algorithm in [8] and [9], where the impact of the presence of the series compensation was studied and improved using the Intelligent Firefly (IFA) algorithm in [10]. Artificial Bee Colony (ABC) hybridization and Particle Swarm Optimization (PSO) were implemented by [11]. The Seeker Optimization Algorithm (SOA) was used in [12]. The PSO with Time-Varying Acceleration Coefficients (PSO-TVAC) is studied by [13]. The Genetic Algorithm (GA) in hybridization with (GA-NLP) have been used by [3] [14], respectively. Grey Wolf Optimizer (GWO) and Enhanced Grey Wolf Optimizer (EGWO) are used in [15]. The Electromagnetic Field Optimization (EFO) algorithm and its modified version (MEFO) were used in [16]. The Adaptive Differential Evolution algorithm (ADE) and the Modified Adaptive Differential Evolution Algorithm (MADE) in [17] and [18], respectively. Harmony Search Algorithm (HAS) by [19]. Gradient-Based Optimizer (GBO) was used in [20]. Imperialistic Competition algorithm in [23]. Cuckoo Search Algorithm (CSA). The Firefly Algorithm (FFA) and the hybrid CSA-FFA were used in [24]. All these methods have been used to solve the problem of over-current coordination.

In this article, the Equilibrium Optimizer (EO) algorithm is used to be compared to other algorithms presented in the literature that use multiple topologies. Although the EO algorithm was introduced in [25], it still has not yet been applied in the field of optimal coordination of relays at maximum current.

The following points summarize the contributions of this paper as follows:

- The EO algorithm is used to solve the problem of optimal coordination of DOCRs relays, and its performance is tested and compared with different methods.
- EO is tested on 3-bus, 4-bus, 8-bus and 15-bus test systems, the problems are successfully resolved in most cases.
- EO hybridization with LP, NLP, and MINLP formulations is applied to improve convergence speed by reducing the required number of iterations and calculation time.
- The EO technique is able to find the optimal global settings.

This paper is organized as follows: Sec. 2. presents the formulation of the problem of directional coordination. The description of the optimization method used is presented in Sec. 3. The numerical results of the simulation are illustrated in Sec. 4. Finally, a conclusion and perspectives are

2. Problem Formulation

The main purpose of directional overcurrent relay coordination is to ensure the security and reliability of the electric power system [15]. This is achieved by determining the optimal relay settings that correspond to the minimum objective function while also preserving the proper functioning of the protection system. In other words, the primary relays must first eliminate the defect that occurs in the protected area; if not, the backup relays must operate to open the circuit after a predefined coordination time in case of failure of the primary relays.

2.1. Objective Function

The objective function can be defined as follows [12]:

$$OF = \sum_{i=1}^{n} OT_i, \tag{1}$$

where OT_i is the primary operating time of i^{th} relay, w is a factor that presents the fault appearing probability, n is the number of relays, the operating time can be defined as follows:

$$OT_i = \frac{a}{PSM^b - 1} TDS_i, \tag{2}$$

where a and b are constant parameters related to the characteristics of the relays, and PSM is defined as:

$$PSM = \frac{I_F}{I_{Pu}}, \tag{3}$$

where PSM is the plug setting multiplier, I_F is the fault current, I_{Pu} is the pickup current.

2.2. Constraints

- Bounds on TDS:

$$TDS_{i\,\min} \leq TDS_i \leq TDS_{i\,\max}, \tag{4}$$

where $TDS_{\min}$ and $TDS_{\max}$ are the minimal and maximal time dial setting respectively.

- Bounds on PS:

$$PS_{i\,\min} \leq PS_i \leq PS_{i\,\max}, \tag{5}$$

where $PS_{\min}$ and $PS_{\max}$ are minimal and maximal plug setting of the relay.

- Bounds on OT:

$$OT_{i\,\min} \leq OT_i \leq OT_{i\,\max}, \tag{6}$$

where $OT_{i\,\min}$ and $OT_{i\,\max}$ are the limits of the operating time of the relay.

- Coordination constraint:

$$OT_s - OT_P \geq CTI, \tag{7}$$

where OT_S is the primary operating time, OT_P is the backup operating time, CTI is the coordination time interval.

- Relay Characteristic constraints:
The constants a and b shown in Eq. (2) are related to the type of the relay used as shown in Tab. 1.

Tab. 1: Constants of relay characteristic.

Relay characteristic	a	b
Standard inverse	0.14	0.02
Very inverse	13.50	1.00
Extremely inverse	80.00	2.00

The standard inverse IDMT characteristic curve is used for this study.

2.3. Penalty and Constraint Violation

The solutions might have an infeasible tripping time. Hence, a penalty term is included into the OF to ensure that the relay tripping time is more than or equal to a certain value OT_{min} [20], and to avoid any violation of coordination constraints:

$$OF = \sum_{i=1}^{n} OT_i^p + \sum_{k=1}^{m} Penalty(k), \tag{8}$$

where n is the number of relays and m is the number of relay pairs (P/S).

Penalty(k) is expressed as follows:

$$Penalty = \begin{cases} \xi\,|CTI - \Delta_k| & \text{si} \quad \Delta_k \leq CTI, \\ 0 & \text{si} \quad \Delta_k \geq CTI, \end{cases} \tag{9}$$

where $\Delta T_k = T_k^{backup} - T_k^{primary}$ and ξ is the penalty factor [17], the penalty term is used in some cases in this study to obtain better results.

3. Equilibrium Optimizer

The Equilibrium Optimizer (EO) [25] is one of the recent physical-based optimization algorithms inspired by the physical mass balance equation. It describes the equilibrium and dynamic states of mass balance models. Furthermore, because of its high exploration and exploitation properties, the EO algorithm has the advantage of being able to change the solution randomly [26]. The particles and concentrations in EO that indicate the search agents are identical to the particles and positions in PSO. To eventually achieve the equilibrium state (optimal outcome), the search agents randomly update their concentration in relation to the best-so-far solutions, namely, equilibrium candidates. The primary premise of EO is described in detail below [26].

3.1. Initialization

Similar to many other metaheuristic algorithms, the EO algorithm requires the creation of an initial population. The lower and upper bounds must be set to allow the population to search within the specified bounds as specified below:

$$C_i^d = C_{\min} + rand_i^d\left(C_{\max} - C_{\min}\right), \; i = 1, 2, \ldots, D, \tag{10}$$

C is the position of the particle, N is the number of particles and D is number of dimensions. $C_{\max}$, $C_{\min}$ are the maximum and minimum values for the dimensions respectively. $rand$ is a random vector between [0, 1].

Then the population will be evaluated with the fitness function to identify 4 best so far solutions [27].

3.2. Equilibrium Pool

The previous four best so far particles and their average are used to construct the equilibrium pool as follows:

$$C_{eq,pool} = \{C_eq(1), C_eq(2), C_eq(3), C_eq(4), C_eq(ave)\}. \tag{11}$$

These five promising candidates stored in the equilibrium pool are used to update the position of the particles in each iteration by a random selection from the equilibrium *pool*, see Fig. 1, where $Ceq, pool$ is the the equilibrium pool; $Ceq(1)$, $Ceq(2)$, $Ceq(3)$, $Ceq(4)$ is the four best-so-far candidates; and $Ceq(ave)$ is the average of four best-so-far candidates.

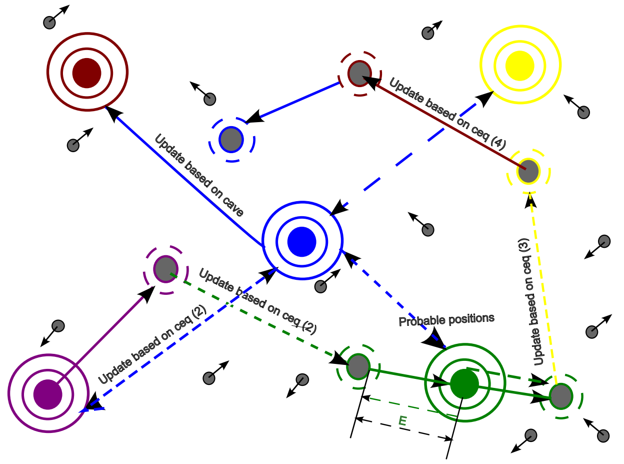

Fig. 1: Equilibrium candidates' collaboration [28].

3.3. Exponential Term

The exponential term is the factor that helps EO to keep a feasible balance between exploration and exploitation. It is defined as follows:

$$F = \exp(-\lambda(t - t_0)), \tag{12}$$

where λ is a random vector between [0,1] and t is calculated as:

$$t = \left(1 - \frac{Iter}{MaxIter}\right)^{\left(\alpha\frac{Iter}{MaxIter}\right)}, \tag{13}$$

where $Iter$ is the current iteration, $MaxIter$ is the maximum number of iterations. α is a constant used to control the exploitation and t_0 is a parameter used to control the exploitation and exploitation as following:

$$t_0 = \frac{1}{\lambda}\ln\left(\beta sign\left(r - 0.5\right)\left[1 - \exp\left(-\lambda t\right)\right]\right) + t, \tag{14}$$

where r is a random vector between [0, 1], β is the constant used to control the exploration capability, when β is higher, the exploration increases; α, β are selected to be 1 and 2, respectively.

By substituting Eq. (14) into Eq. (12), the final exponential term obtained is:

$$F = \beta\text{sign}\left(\left(r - 0.5\right)\exp\left(-\lambda t\right) - 1\right). \tag{15}$$

Figure 2 also illustrates the flowchart of Equilibrium Optimizer.

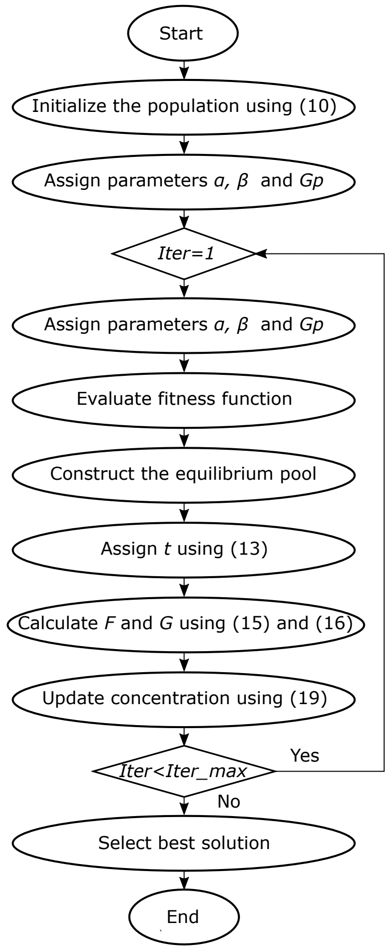

Fig. 2: Flowchart of Equilibrium Optimizer.

3.4. Generation Rate

Generation Rate is one of the main factors in EO. It helps to improve the exploration feature of EO. It is formulated as follows:

$$G = G_0\exp\left(-\lambda\left(t - t_0\right)\right) = G_0 F, \tag{16}$$

$$G_0 = GCP\left(C_{eq} - \lambda C\right), \tag{17}$$

$$GCP = \begin{cases} 0.5r_1 & \text{if} \quad r_2 \geq GP, \\ 0 & \text{if} \quad r_2 \leq GP, \end{cases} \tag{18}$$

where r_1, r_2 are two random vectors between [0, 1], and GCP is the eneration rate control parameter.

The updating rule of EO is defined as follows:

$$C = C_{eq} + \left(C - C_{eq}\right)F + \frac{G}{\lambda V}\left(1 - F\right). \tag{19}$$

3.5. Memory Saving

This mechanism resembles to P_{best} concept in PSO. If the fitness value attained by the particle in the current iteration is better than the previous iteration, then the particle with better fitness will be saved and stored in P_{best} [27].

4. Test Result and Discussion

The EO was tested on three separate test situations in this study. Among these test cases, the 3-bus system employs the LP optimization model for relay coordination, in which the TDS is the only variable to optimize while keeping the PS value constant, and hence initial PS values are required. The second test case, the 4-bus and 15-bus system, employs NLP, using TDS and IP as design variables, the latter accepting continuous values. Finally, in the third test case, the 8-bus system displays formulation, which is continuous non-linear or Mixed-Integer Programming (MINLP), where the variables to be optimized are TDS and PS. The distinction between the two formulations is that PS accepts continuous values in NPL, whereas PS accepts discrete values in MINLP. The test cases involve comparing the results with various algorithms, including GA, HAS, GA-NLP, CSA, FFA, PSO, HHO, Jaya, and BBO. The simulation is run on a Windows 10 platform with 12 GB of RAM and a Core (TM), 2.7 GHz processor using the MATLAB version (R2016b).

4.1. Case 1: 3-Bus Test Case

In the first case with LP formulation, the Equilibrium Optimizer algorithm is tested and validated on the 3-bus [5], [12], and [19] system as shown in Fig. 3.

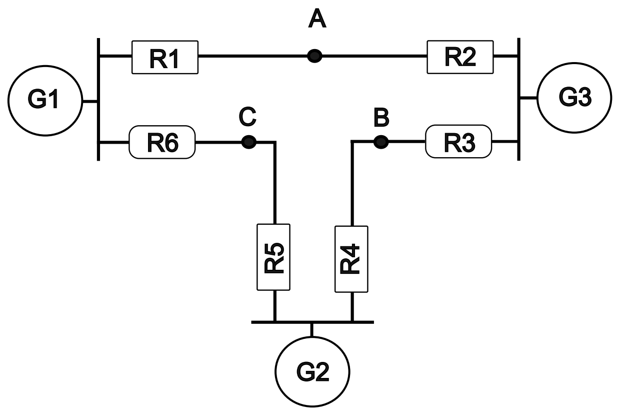

Fig. 3: IEEE 3-bus DOCRs coordination problem model.

Figure 3 depicts the single line diagram of the three-bus system, which has three lines, three generators, and six DOCRs. The system information for each line's three faults, including the CT ratio, P/B relay pairs, and fault current going through relays, is provided in Tab. 2. In this study, the PS of each relay is assumed to be fixed at 2 for relays 1 and 2; 2.5 for relays 3, 4, and 5 accordingly; and 1.5 for relay 6. This assumption is based on the CT ratio and the range of possible PS. CTI and the minimal working time of a relay are both thought to be 0.2 seconds. TDS is measured consistently between 0.1 and 1.1. For this test case, EO parameters as Population size $(Pop) = 20$, constant used to control the exploitation $\alpha = 1$, constant used to control the exploration capability $\beta = 2$, Generation rate control parameter $GCP = 0.5$ number of iteration $(Itermax) = 200$.

Tab. 2: P/B pairs and related parameters for the 3-bus system [5] and [12].

Primary Relay				Backup Relay	
Relay	CT	PS	IF(A)	Relay	IF(A)
1	300/5	2.0	1987.90	5	175.00
2	200/5	2.0	1525.70	4	545.00
3	200/5	2.5	1683.90	1	617.22
4	300/5	2.5	1815.40	6	466.17
5	200/5	2.5	1499.66	3	384.00
6	400/5	1.5	1766.30	2	145.34

Because PS is fixed in this scenario, only TDS is considered as the variable to be optimized. The optimal value of TDS, OF value created using (8), and convergence time obtained by adopting LP formulation hybrid with EO are tabulated in Tab. 3. The best result of the 3-bus system is given by EO, with a value of OF equal to 1.5146 s, while all other published methods yield almost the same answer $(OF = 1.5981$ s) for the 3-bus test system without violation of any constraint. According to Tab. 3, the GA converges in 29.254 s and 65 iterations, the CSA converges in 14.132 s and 51 iterations, the FFA converges in 19.672 s and 57 iterations, and the HSA converges in 12.465 s and 46 iterations. On the other hand, EO requires 6.35 s and 200 iterations to converge near optimal solution which is less than all other the literature published methods.

Tab. 3: Optimal setting result for 3-bus system.

Relay N°	GA [19]	FFA [24]	CSA [24]	HAS [19]	EO
1	0.1148	0.1143	0.1143	0.1142	0.1000
2	0.1001	0.1000	0.1000	0.1000	0.1000
3	0.1076	0.1074	0.1074	0.1074	0.1000
4	0.1002	0.1000	0.1000	0.1000	0.1000
5	0.1001	0.1000	0.1000	0.1000	0.1000
6	0.1194	0.1125	0.1125	0.1125	0.1000
OF (s)	1.6184	1.5981	1.5981	1.5981	1.5146
Iter	65	57	51	46	200
Time (s)	29.254	19.672	14.132	12.465	6.35
Pop	50	15	15	30	20

Additionally, the primary and backup operating tome are tabulated in Tab. 4.

4.2. Case 2: 4-Bus Test Case

In the second case with NLP formulation, the topology, is a 4-bus system is different from the previous cases, both near-end and far-end 3ϕ fault locations are considered in Fig. 4. The system comprises 4 buses, 4 branches, and 8 DOCRs [5]. The parameters of EO

Tab. 4: Operating time and CTI for the 3-bus system by LP formulation.

P/R	B/R	OTp	OTs	CTI
1	5	0.2644	1.2520	0.9876
2	4	0.2305	0.5404	0.3099
3	1	0.2410	0.4858	0.2448
4	6	0.2738	0.5041	0.2304
5	3	0.2516	0.5222	0.2707
6	2	0.2534	1.176	0.2931

selected are $Pop = 15$ and $Max\_iter = 7000$, with 16 design variables the TDS limits are 0.05 and 1.1, and for the PS 1.25 and 1.5, respectively. The minimum and maximum Operating times are 0.05 and 1, respectively. The CTI is set to be 0.3 s.

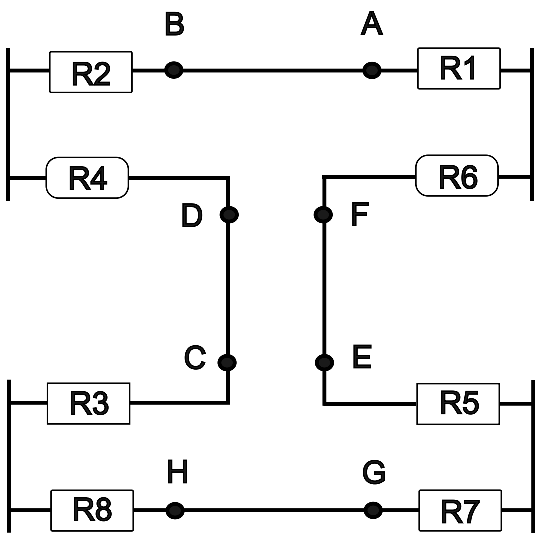

Fig. 4: IEEE 4-bus system DOCRs coordination problem model.

The objective function is expressed as follows:

$$\sum_{p=1}^{m} T_{pr,p}^{near} + \sum_{q=1}^{n} T_{pr,q}^{far}, \tag{20}$$

where T_{jk} is the operating time of the j^{th} backup for a 3ϕ fault which happens at the k^{th} location. T_{ik} is the operating time of the i^{th} primary for a 3ϕ fault which happens at the k^{th} location.

$$T_{jk} - T_{ik} \geq CTI, \tag{21}$$

where T_{jk} and T_{jk} can be computed by the following equations:

$$T_{pr,p}^{near} = TDS_p \frac{0.14}{\left(\frac{a_p}{PS_p \cdot b_p}\right)^{0.02} - 1}, \tag{22}$$

$$T_{pr,q}^{far} = TDS_q \frac{0.14}{\left(\frac{c_p}{PS_q \cdot d_p}\right)^{0.02} - 1}, \tag{23}$$

$$T_{ik}^{p} = TDS_i \frac{0.14}{\left(\frac{g_p}{PS_i \cdot h_p}\right)^{0.02} - 1}, \tag{24}$$

$$T_{jk}^{q} = TDS_j \frac{0.14}{\left(\frac{e_p}{PS_j \cdot f_p}\right)^{0.02} - 1}, \tag{25}$$

The constants a, b, c, d, e, f, g and h are given by the manufacturer of the relays [5].

Related constants (a, b, c, d, e, f, g and h), are given in [5]. The primary operating time of each relay (Ti) should be bounded between in [0.05, 1.0]. Tab. 5 shows the optimized results by EO, HHO [5] and Jaya [5], using the objective function of formula (20). However, EO is able to achieve feasible solution with no violations in every independent run time. In the Tab. 5, EO reaches its optimal value within 7000 iterations, with a value of OF equal to 3.6983 s, HHO and Jaya reaches its optima within 2000 iterations, with a value of OF 3.7539 and 3.7020 s, respectively. Is proves the convergence rate of Jaya and HHO are much faster than EO. However, the robustness and consistency of HHO and Jaya is not as good as that of EO, as shown in Tab. 5.

Tab. 5: Optimal setting for 4-bus system.

Relay N°	Jaya [5]		HHO [5]		EO	
	TDS	PS	TDS	PS	TDS	PS
1	0.0500	1.3207	0.0500	1.2969	0.0500	1.2513
2	0.2122	1.5000	0.2297	1.2500	0.2155	1.4411
3	0.0500	1.3238	0.0500	1.2500	0.0500	1.2500
4	0.1539	1.4760	0.1634	1.2500	0.1603	1.3389
5	0.1267	1.5000	0.1420	1.2500	0.1314	1.3951
6	0.0500	1.2500	0.0500	1.2500	0.0500	1.2520
7	0.1350	1.5000	0.1467	1.2500	0.1363	1.4464
8	0.0500	1.3142	0.0500	1.2500	0.0501	1.2539
OF (s)	3.7020		3.7539		3.6983	
Iter	2000		2000		7000	
Time (s)	2.9355		7.2515		1.3518	
Pop	50		50		15	

Table 6 shows the operating time and CTI for EO algorithm, we can see that CTI constraints are satisfied in all P/B pairs.

Tab. 6: Operating time and CTI for the 4-bus system by NLP formulation.

P/R	B/R	EO		
		OTp	OTs	CTI
1	5	0.0960	0.3964	0.3005
1	5	0.1120	0.5018	0.3899
3	7	0.1540	0.4548	0.3009
3	7	0.1758	0.5247	0.3489
4	1	0.0500	0.5274	0.4774
6	2	0.1633	0.5160	0.3509
6	2	0.1583	0.4643	0.3042
8	4	0.1730	0.5673	0.3944
8	4	0.1342	0.4358	0.3017

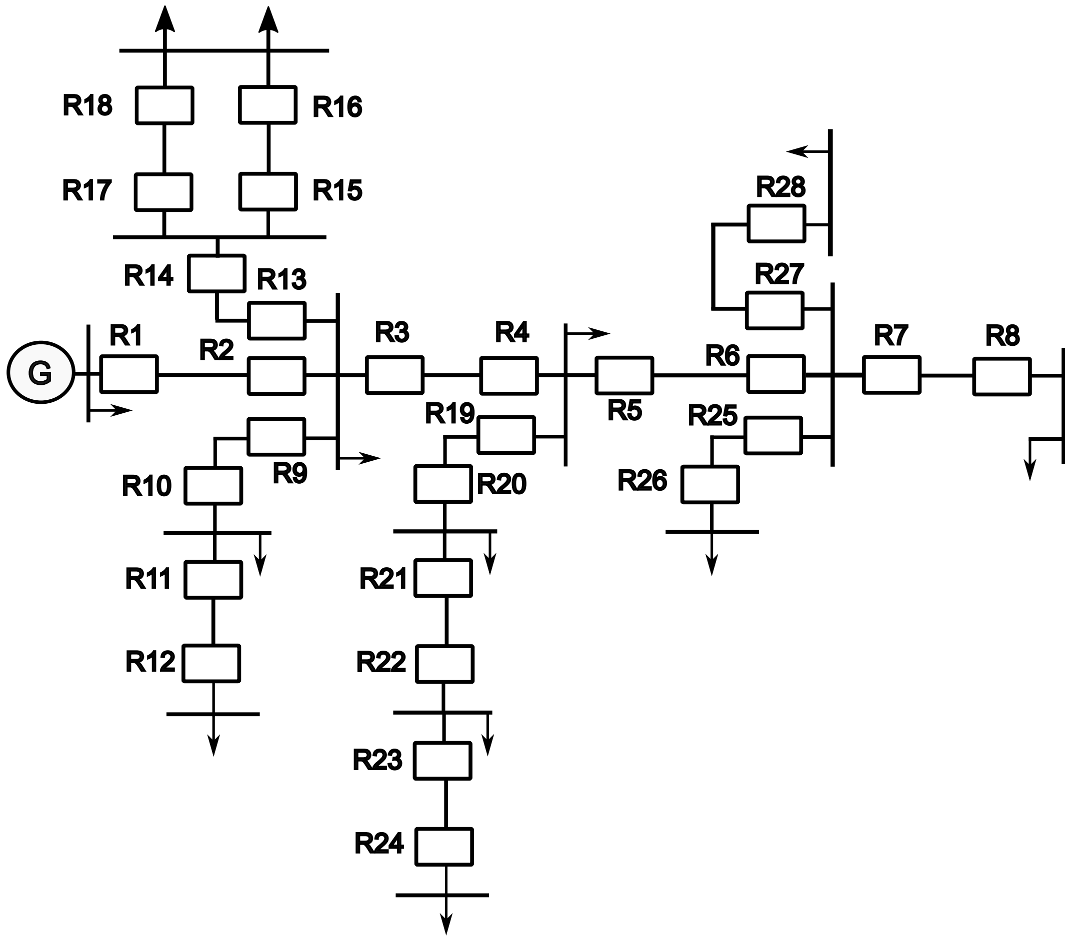

Fig. 5: IEEE 15-bus system DOCRs coordination problem model.

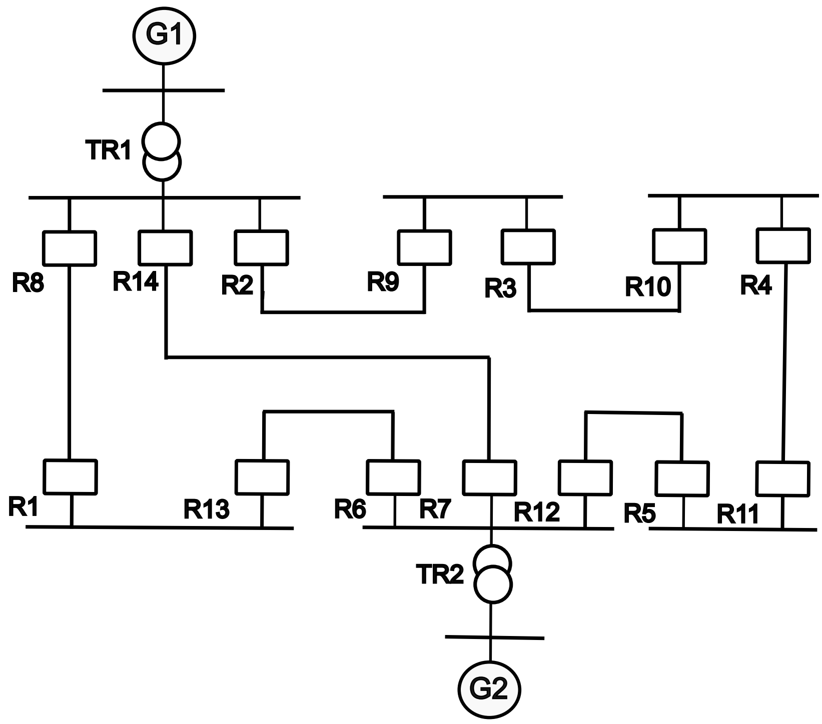

Fig. 6: IEEE 8-bus system DOCRs coordination problem model.

4.3. Case 3: 15-Bus Test Case

In the third topology with NLP formulation, the EO is applied on 15 node radial network system [29], 1 generator, including a total of 13 loads are considered. The system consists of 28 digital overcurrent relays shown in Fig. 5. The parameters of EO are set as follows: $Pop = 15$, $Max\_iter = 2000$, and the relays have the same current transformer ration 500 : 1. The $OTi_{\min}$ and $OTi_{\max}$ is set to 0.1 and 4 s, respectively; the $TDS_{\min}$ and $TDS_{\max}$ are 0.1 and 1.1, respectively; $PS_{\min}$ and $PS_{\max}$ are 0.5 and 2.5, respectively [30]. The P/B relationships for this system and the technical data are given in [29].

The detailed results obtained are shown in Tab. 7, shows that EO gives a better value of the objective function of 9.6341 s, with converge time equal to 0.3980 s, against 26.189 s for objective function, with converge time 4730.86 s for PSO. So, the total operating time obtained by EO is less than that of PSO by 63.21 %. Moreover, the solutions are optimized with no constraint violations.

Tab. 7: Optimal setting obtained for 15-bus system.

Relay N°	PSO [29]		EO	
	TDS	PS	TDS	PS
1	0.74394	0.54999	0.5472	1.5214
2	0.32216	1.2551	0.1110	0.5000
3	0.3416	1.5153	0.4898	0.5166
4	0.55245	2.4141	0.1009	0.5101
5	0.36342	0.60859	0.2660	0.5000
6	0.4309	1.0805	0.1000	0.7230
7	0.11188	1.2611	0.1017	0.5000
8	0.2726	1.822	0.1248	0.5127
9	0.45395	1.1148	0.2699	0.6016
10	0.15359	1.3933	0.1269	0.5195
11	0.32133	0.50089	0.1000	0.5000
12	2.6418	2.4727	0.1082	0.5427
13	0.32088	1.9075	0.2503	0.5240
14	0.73899	2.1497	0.1030	0.5000
15	0.42632	0.79222	0.1026	0.5090
16	0.54396	0.67839	0.1080	0.8908
17	0.21794	0.61987	0.1085	0.6911
18	0.12037	1.1896	0.1288	0.5682
19	0.31997	0.66671	0.3027	0.6928
20	0.56566	1.1323	0.1002	0.5338
21	0.26376	0.60754	0.1849	0.6578
22	0.14313	1.8741	0.1176	0.5708
23	0.12496	0.7978	0.1000	0.5000
24	0.55302	1.3848	0.1063	0.5094
25	0.22254	0.65529	0.1016	0.7156
26	0.2904	1.6316	0.1036	0.6905
27	0.12471	0.77885	0.1192	0.5324
28	0.10277	2.4925	0.1054	0.5701
OF (s)	26.189		9.6341	
Iter	10000		2000	
Time (s)	4730.86		0.3890	
Pop	60		15	

Table 8, shows that the constraints are respected for the EO algorithms, and that there is no violation for all the pairs of relays.

Tab. 8: Primary and backup operating time and CTI for 15-bus system.

P/R	B/R	OTp	OTs	CTI
1	-	1.0890	-	-
2	-	0.1952	-	-
3	1	0.8692	1.0890	0.2198
4	-	0.2002	-	-
5	3	0.5249	0.8692	0.3442
6	-	0.2454	-	-
7	5	0.2195	0.5249	0.3054
8	-	0.2931	-	-
9	1	0.4998	1.0890	0.5891
10	-	0.2532	-	-
11	9	0.1973	0.4998	0.3025
12	-	0.2401	-	-
13	1	0.4459	1.0890	0.6430
14	-	0.2031	-	-
15	13	0.2035	0.4459	0.2424
16	-	0.2873	-	-
17	13	0.2372	0.4459	0.2087
18	-	0.2901	-	-
19	3	0.6623	0.8692	0.2068
20	-	0.2210	-	-
21	19	0.4386	0.6623	0.2237
22	-	0.2871	-	-
23	21	0.2328	0.4386	0.2058
24	-	0.2661	-	-
25	5	0.2484	0.5249	0.2764
26	-	0.2720	-	-
27	5	0.2628	0.5249	0.2621
28	-	0.2478	-	-

4.4. Case 4: 8-Bus Test Case

The fourth case, is study 8-bus system is modelled as Mix Integer Nonlinear Programming Problem (MINLP). The system contains 8 buses, 2 transformers, 2 generators, and 14 relays. The value of TDS is continuous varies between 0.1 and 1.1, the PS is considered discrete from 0.5, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, and the CTI is selected at 0.3 s [5]. The system consists of 14 digital overcurrent relays shown in Fig. 6. The parameters of EO chosen are $Pop = 20$ and $Max\_iter = 3000$ iterations. The primary and backup fault currents are given in [5]. Due to the severe constraints and small number of discrete PS values in this scenario, it is difficult to find optimal solutions.

As shown in Tab. 9, We notice that the time obtained by the HHO algorithm violates the selectivity constraint with a value of 7.2849 s, converges in 14.6635 s and 2000 iterations. The BBO, converges in 2065.02 s and 10000 iterations with an optimal OF value of 10.5495 s. The Jaya, converges in 2.1031 s and 2000 iterations with an optimal OF value of 10.325 s.

On the other hand, EO requires 0.5962 s and 3000 iterations to converge near optimal solution 8.9451 s, which is less than all other the methods published in the literature (BBO, Jaya and HHO).

The Tab. 10, shows the operating time and CTI.

Tab. 9: Optimal setting obtained for 8-bus system.

Relay N°	BBO [6]		Jaya [5]		HHO[5]		EO	
	TDS	PS	TDS	PS	TDS	PS	TDS	PS
1	0.14239	2.50	0.1000	2.50	0.1000	2.50	0.1002	2.5
2	0.38159	2.00	0.4409	1.00	0.2484	2.50	0.2843	2.5
3	0.29326	2.00	0.4585	0.50	0.2691	1.50	0.2293	2.5
4	0.22081	2.00	0.1900	2.00	0.1000	2.50	0.1620	2.5
5	0.11834	2.50	0.1030	2.50	0.1000	1.00	0.1000	2.5
6	0.24271	2.00	0.3447	0.50	0.3484	0.50	0.1748	2.5
7	0.32704	2.00	0.2776	2.50	0.2901	1.50	0.2593	2.5
8	0.21560	2.00	0.2638	2.00	0.1616	2.50	0.1834	2.5
9	0.22933	2.00	0.2482	1.50	0.1000	2.50	0.1586	2.5
10	0.31500	1.50	0.3507	1.00	0.1050	2.50	0.1986	2.5
11	0.27815	2.00	0.2665	2.00	0.1636	2.50	0.2063	2.5
12	0.36940	2.00	0.3163	2.50	0.2402	2.50	0.2857	2.5
13	0.10363	2.50	0.2555	1.00	0.1000	2.50	0.1081	2.5
14	0.35736	2.00	0.3205	2.00	0.2043	2.50	0.2649	2.5
OF (s)	10.5495		10.325		7.2849		8.9451	
Time (s)	2065.02		2.1031		14.6635		0.5962	
Iter	10000		2000		2000		3000	
Pop	50		50		50		20	

Tab. 10: Optimal setting obtained for 8-bus system.

P/R	B/R	OTp	OTs	CTI
1	6	0.4096	0.7146	0.3049
2	1	0.8494	1.3773	0.5278
2	7	0.8494	1.1511	0.3016
3	2	0.7187	1.0987	0.3799
4	3	0.6046	0.9148	0.3102
5	4	0.4978	0.8065	0.3186
6	5	0.5152	1.0066	0.4913
6	14	0.5152	1.1824	0.6672
7	5	0.6886	1.0066	0.3179
7	13	0.6886	1.5134	0.8248
8	7	0.5410	1.1511	0.6099
8	9	0.5410	1.0274	0.4863
9	10	0.5968	0.9649	0.3681
10	11	0.7308	1.0318	0.301
11	12	0.7685	1.0784	0.3098
12	13	0.8552	1.5134	0.6582
12	14	0.8552	1.1824	0.3272
13	8	0.4637	0.7863	0.3226
14	1	0.7047	1.3773	0.6725
14	9	0.7047	1.0274	0.3226

5. Conclusion

In this paper, the EO was successfully applied to solve the Directional Overcurrent relays Coordination Problem (DOCRs). In the experiments our test systems included 3-bus, 4-bus, 8-bus, and 15-bus (one LP case, two NLP cases, and one MINLP cases). Also, the effectiveness of proposed method was verified for linear, nonlinear and mixed-integer nonlinear optimization model. The obtained results using the EO, is compared with GA, HHO, FFA JAYA, HAS, CSA, PSO and BBO. The comparative study exhibits that the proposed method substantially minimizes the total operating time of relays compared to other well-established methods. To make comparisons easier, we put the value of N pop in this study at 15, 20. The authors are considering a different approach to figuring out N pop, one that may use a self-adaptive process defined by the population's capacity for change rather than predetermining the value of N pop. Additionally, the impact of the constraint-handling method on the effectiveness, efficiency, and clarity of the solution was thoroughly studied, and it was discovered that the penalty function may strike a balance between these requirements. The EO algorithm was determined to be the best of the five algorithms examined in this study based on the investigations conducted in it on the following counts: Among the best values acquired by the four algorithms taken into consideration in the study, the best value achieved by EO is always the lowest.

- The best value produced by EO is essentially impervious to changes in the EO's settings.
- EO provides the lowest value of the goal function even when the relays' characteristic curves disagree.
- In comparison to the other four approaches, the results obtained by EO are relatively predictable due to the low standard deviation value.

As a consequence, among the five algorithms examined in this paper, the EO can be regarded as the one that is best appropriate for the coordination of DOCRs. Future research should focus on how to improve the objective function value while also quickening EO's pace of convergence. To further advance EO application in this area, bigger test systems of the DOCRs coordination challenge, such as 33-bus, 50-bus, and 100-bus are planned to be examined in the upcoming study.

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Author Contributions

Both G.K. and M.F. contributed substantially to the development of the concept of optimum relay coordination. Both GK. and S.N.E. contributed for analysis and interpretations. Both G.K. and D.L. contributed to the final version of the manuscript. M.F. supervised the work. Both G.K. and M.F. agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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