Journal of Operation and Automation in Power Engineering

Vol. 11, No. 3, Oct.. 2023, Pages: 151-161

http://joape.uma.ac.ir

An Improved Optimal Protection Coordination for Directional Overcurrent Relays in Meshed Distribution Networks with DG Using a Novel Truth Table

H. Shad, M. Gandomkar, J. Nikoukar*

Department of Electrical Engineering, College of Electrical Engineering and Computer, Saveh Branch, Islamic Azad University, Saveh, Iran

Abstract- *To assure the security and optimal protection coordination in meshed distribution networks, clearing faults swiftly and selectively is an essential priority. This priority, when hosting distributed generations (DGs), becomes the main challenge in order to avoid the unintentional DGs tripping. To overcome the mentioned challenge, this paper establishes a truth table to select new settings of directional overcurrent relays (DOCRs) characteristics which can be defined by users. It concentrates on minimizing the overall relays operating time. Typically, the conventional coordination between pair relays is achieved by two settings: time dial setting (TDS) and pickup current (Ip). Besides these adjustments, the suggested approach, considered the two coefficient constant of the inverse-time characteristics, namely the relay characteristics (A) and the inverse-time type (B), as continuous to optimize. Thus, more flexibility is attained in adjusting relays features. In addition, the inclusion of user-defined settings on numerical DOCRs, not only decreases the overall operating time of relays, but also improves the performance of the backup relays against the fault points. This approach illustrates a constrained non-linear programming model tackled by the combined particle swarm optimization (PSO) and whale optimization algorithm (WOA). The efficiency of the suggested approach is assessed though the IEEE 8-bus and the distribution portion of IEEE 30-bus system with synchronous-based DG units. The obtained results demonstrate the performance of approach and will be discussed in depth.*

Keyword: Protection Coordination; Numerical DOCRs; Meshed Distribution Networks; synchronous-based DG; Combined PSO-WOA.

NOMENCLATURE

T	The Overall Operating time of DOCRs (s)
t	Operating time of DOCRs (s)
TDS	Time Dial Settting (s)
I_{SC}	The short circuit current seen by relay (p. u.)
I_P	The pickup current which is relay start operation (p. u.)
A, B	Coefficients of current-time characteristic curve for DOCRs (s)
F, f	The total number of fault point and count the feasible fault points
N	The total number of DOCRs
i, k	Identifier the primary and backup DOCRs
CTI	The coordination time interval between backup and primary relay for fault at point f (s)
t^P, t^B	Operating time of primary/ backup DOCRs (s)
t_{min}, t_{max}	The maximum and minimum Operating time of DOCRs (s)
I_L	The load current (p.u.)
V_i^t, V_I^{t+1}	The velocity of i-th particle at iteration number (t) and ($t+1$)
w	The inertia weight
$c1$, $c2$	The cognitive and social parameter
$r1$, $r2$	The random number
$Whale-Pos_i^t$	The bubble-net attacking method for whale position path during optimization
$Gbest_i^t$	Global best position of i-th particle
X_i^t, X_I^{t+1}	The position vector of the i-th particle at iteration number (t) and ($t+1$)

Received: 07 Feb. 2022
Revised: 06 Mar. 2022
Accepted: 30 Apr. 2022
∗Corresponding author:
E-mail: gandomkar@iau-saveh.ac.ir (M. Gandomkar)
DOI: 10.22098/joape.2023.10320.1732
Research Paper

1. INTRODUCTION

Due to the integration of DGs in meshed distribution networks, an accurate and fast-response protection scheme to guarantee a safe operation against the possible faults is a high priority. In these networks, unlike the radial distribution networks which are presented with unidirectional fault currents, and where only one backup relay is adequate for each primary relays, two or more backup relays are required to provide a safe protection scheme. In this protection scheme, if the main protection relay does not operate to isolate the area affected by the fault, after a specific time which is called CTI, the backup relay should operate [1, 2]. In the field of power system protection, the optimal protection coordination (OPC) of DOCRs in the meshed distribution networks is a challenging task; therefore, there are some method have been recommended for this aim.

Numerous solutions have been conducted to choose the best time-current characteristic setting of DOCRs. In references [3, 4], linear programing (LP) and mixed integer linear programming (MILP) with disjunctive inequalities were employed for optimization, and the TDS and Ip of relays were considered as the optimization variables. Despite their simplicity and speed, these approaches are relatively complex and do not have sufficient efficiency due to the non-linear setting of the relays. In [5], to optimize the variables of relays, two phase simplex method with PSO has been adopted for solving the non-linear DOCRs coordination problem. Both the conventional optimization techniques can be trapped at the local minima and fail to achieve the global maxima. Also, the rate of convergence of such optimization algorithms are slow with the increase of the system size. Several heuristics, metaheuristics and evolutionary optimization algorithms have been proposed to find the optimal settings of relay variables for reduce the overall relays operating time. DOCRs inverse-time characteristic would be set by TDS and Ip settings, so, An OBL-FOCTO [6], modified PSO [7] and imperialistic competition algorithms [8] are used to solve the coordination problem. Slime mould algorithm (SMA) assuming continuous values for variable settings [9]. However, most of the heuristic evolutionary algorithms require more computational time and also suffer from premature convergence. Till date, a significant effort has been put by the researchers for solving the optimal relay coordination problems of DOCRs. Next, the drawback could be overwhelmed by the application of hybrid algorithms in [10- 14]. Simulated annealing-linear programming (SA-LP) and interval linear programming-differential evolution optimization (LP-DE) has been studied in [10, 11]. The optimal settings and minimum operation time of primary/backup DOCRs were found by Dual feasible direction-finding nonlinear programming, grey wolf optimization (GWO) and harris hawks optimization with sequential quadratic programming (HHO-SQP) in [12- 14]. Authors in [15], use the fault current limiter (FCL) in path with DGs, to attempted the protection re-coordination. However, better results have been obtained through these optimization approaches rather than the linear and metaheuristic ones, they were not flexible. Numerical relays are also deployed for working on different matters.

Numerical DOCRs (N-DOCRs) allowed the users to define customized time-current characteristics (TCCs) graphically which resulted in the development of coordination strategy [16, 17]. Due to this feature, new coordination approaches called user-defined or non-standard characteristics were proposed. In Ref. [18] user-defined dual-setting DOCR with hybrid time and current-voltage characteristics (UDDORs-TCV) proposed for protection scheme. The suggested model is formulated in a constrained non-linear optimization fashion, which is tackled by MINLP solver of general algebraic modelling systems (GAMS) software. Dual setting DOCRs (DS-DOCRs) has different settings of TDS and Ip for forward and reverse directions in order to cope with the effect of reverse DG fault current contribution. Fuzzy adaptive setting and minimum-constrained nonlinear multivariable function were used in [19, 20] to obtain the time-current-voltage characteristic setting.

Although the numerical relays improve the protection parameters, it can also be considered in studies simultaneously using their capabilities. A two-phase optimization of DS-DOCRs and time-current-voltage characteristic with grey wolf optimization (GWO) algorithm was developed to compute the proposed protection coordination index in [21]. The improved solution to find the optimal adjusting of DOCRs by addition of an auxiliary variable to the standard equation studied in [22]. Also, sine cosine algorithm (SCA), adaptive modified firefly algorithm (MFA) are presented are reported in [23, 24] for solving optimization problems. Also, a highly reliable OPC scheme considering nonstandard relay curves studied in [25]. Despite the great achievement in decreasing the relays operating times, the established approaches could be further investigated.

Several studies have been reported for improving the coordination scheme which mainly consists of a better setting of the characteristics for standard and non-standard curves. Invasive weed optimization (IWO) and modified electromagnetic field optimization (EFO) algorithm are developed in [26, 27] for the optimal coordination problem considering various non-standard DOCRs. In [28], the authors present an auxiliary variable in the tripping characteristics of DOCRs which causes more flexibility in setting relay's characteristics for improving the coordination. This constraint is incorporated in [29], using a non-standard curve for enhancing the performance of the DOCRs protection. The non-standard curve modifies the region defined by the characteristic curve. The user-defined characteristics along with using an efficient optimization model in DOCRs, caused relay's efficient time reduction & also increasing in backup relay's efficiency in multi supply meshed distribution network [30]. Although the numerical relays improve the protection parameters, it can also be considered in studies simultaneously using optimal design of hybrid microgrid [31]. Authors in [32] established a hyper-spherical search algorithm (HSSA) to obtain the user-defined characteristic setting for the optimal coordination. Finally, in [33] a comparative overview of different metaheuristic-based optimization methodologies is presented to achieve a proper solution for the coordination problem between each relay pairs to guarantee satisfactory relay settings. Based on the literatures, there are the following major research gaps in the field of OPC strategy of DOCRs in the distribution networks in presents of DGs:

- In most research there is a gap about evolving novel methods smartly selecting the DOCRs characteristics. Thus, to fill the research gap, in this paper a novel truth table proposed based on mixed standard characteristic curves to optimization the relay settings and coordination between primary and backup relay pairs simultaneously.
- The optimal protection re-coordination is used in various pieces of research to improve the protection coordination between pairs DS-DOCRs on distribution network which the relay parameters are set to other values. This is time-demanding because the variable settings should be adjusted in two directions (forward and reverse) using communication link. In some other studies, FCLs are exploited in the distribution network to reduce the inverse effects of DGs on protection coordination. Note that this scheme requires a significant investment cost.
- The major disadvantage of time-current-voltage characteristic for UDDOCRs is that this characteristic depends on the magnitude of the fault voltage. The operating time of each UDDOCRs-TCV is designed in proportion to the voltage drop based on the fault event, so a large voltage drop indicates that the fault is very close to the relay which can lead to loss of OPC.

Following the research gaps, this paper presents an improved (OPC) strategy using a novel truth table and analyzes it using mathematical rules to define the new settings of inverse-time characteristics on numerical DOCRs. The aim of this optimization process is minimizing the overall relays operating time. In this context, the OPC problem consists three variable settings which can be defined by users and depending on each other. This reveals a nonlinear optimization problem which is tackled by the combination of PSO-WOA algorithms. The main advantage of proposed hybrid algorithm is that it smoothly transits from exploration to exploitation. Comprehensive numerical studies are carried out to evaluate the efficiency of the suggested approach. Consequently, some technical constraints are considered in the optimization process, and the list of main contributions are as follows:

- An efficient truth table is established and analysis using mathematical aspects to define the optimal settings of inverse-time characteristics on overcurrent relays;
- A user-defined setting is invented on numerical DOCRs to minimize the overall relays operating time and caring the existing constraints;
- Improve the performance of relays in fast-response to faults with decreasing the operating time;

The following sections of this paper are as follows: Section 2 presents the extracting user-defined settings based on mathematical aspects for numerical DOCRs considering the customized inverse-time characteristics and how to use the combined algorithm. Section 3 shows how the formulation of the OPC problem model is done. Section 4 points out various case studies and discussions about the obtained results by the proposed coordination strategy. Finally, Section 5 demonstrates the conclusion.

2. PROPOSED OPC STRATEGY

2.1. Extracting User-Defined Settings Based on Mathematical Aspects

In this section, the user-defined settings is extracted based on the mathematical aspects. According to IEC 60255 [16, 17] the mathematical non-linear equation describing inverse-time characteristics of DOCRs and operating time can be expressed in (1).

$$t = TDS\frac{A}{\left(\frac{I_{SC}}{I_P}\right)^B - 1} \tag{1}$$

The standard definitions of A and B parameters are also given in Table 1.

Table 1. Conventional coefficient constant of DOCRs

Type of Characteristic	Parameter	
	A	B
Standard Inverse (SI)	0.14	0.02
Very Inverse (VI)	13.8	1
Extremely Inverse (EI)	80	2

Table 2. Different optimization case studies on numerical relaying based on truth table

Case Study	Parameter			
	TDS	Ip	A	B
1	0	0	0	0
2	0	0	0	1
3	0	0	1	0
4	0	0	1	1
5	0	1	0	0
6	0	1	0	1
7	0	1	1	0
8	0	1	1	1
9	1	0	0	0
10	1	0	0	1
11	1	0	1	0
12	1	0	1	1
13	1	1	0	0
14	1	1	0	1
15	1	1	1	0
16	1	1	1	1

As discussed earlier, one of the main advantages of numerical relays allows the user to define new characteristic curve which develops the relays efficiency and flexibility. Accordingly, with some basic functional rules, the user can easily reshape the coefficient constant of inverse-time characteristics (A and B). In user-defined settings, the TDS, Ip, A and B are decision-making variables. As it can be seen, on implemented OPC strategy there are 4 variable setting, thus; $2^n - 1$ case study is for the optimization problem, which are reported in Table 2 (for example, B parameter is optimized in case 2 and likewise Ip and A parameters are optimized in case 7). It is essential to note that the optimization problems usually desire to have the lowest values. In the following, the inverse-time equation of relay that is declared by Eq. (1) is analyzed by considering Table 2 and the mathematical aspects.

The TDS, A, Isc, Ip and B values are 0.1 s, 0.14, 2.7371 p.u., 0.0767 p.u. and 0.02 for R5 in conventional strategy [21, 30], respectively. Increasing some parameters, namely the TDS, Ip and A, increases the operating time, but increase of B, decreases it significantly, shown in Fig. 1 (all parameters increase 0.01). For instance, in case 2, only the B parameter increases to 0.03. By recalling Table 1 and taking TDS constraint between (0.1s- 3s) according to [10, 12, 18, 21- 23, 30], the lower and upper limits of this parameter also A and B are declared. According to equation (1) and due to this fact that the TDS and A have direct effects on each other, the optimization of both is not mathematically logical. It can be easily deduced if assume the A parameter is minimum, and multiple it on maximum value of TDS, the result equals to 0.42 s (0.14×3 s), and vice versa it equals to 8 s (80×0.1 s). In this study, because it intends to use the user-defined feature of the numerical relays, it has been neglected to optimize the TDS parameter. Thus, cases 9-16 are eliminated from optimization. Fig. 2 shows the effect of increasing the parameters on operating time in case 16. Change the Ip parameter, do not set upper or lower the inverse-time curve but increase the operating time as shown with (Y=0.1564).

It is noticed that the case 7 is eliminated too, because both of parameters (Ip and A) increase the operating time. So there are 6 case studies. Since usually optimizing only one parameter, does not achieve the minimum overall operating time of DOCRs, cases 2, 3 and 5 are also removed. Furthermore, by optimizing the two parameters, which have been addressed in the recent studies, the overall operating time is not perceptibly reduced; as the result, cases 4 and 6 are also omitted from the optimization problem. Thus, in this study, only case (8) is used to solve the OPC problem, and the Ip, A and B parameters are optimized.

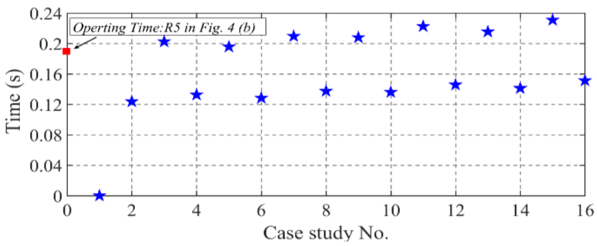


Fig. 1. Comparing the operating time for R5 in conventional strategy [30] versus case studies

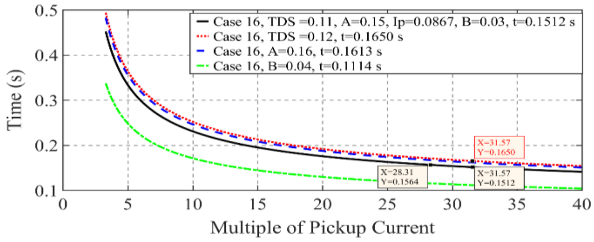


Fig. 2. Effect of increasing the parameters on relay operation time

2.2. Extracting User-Defined Settings Based on Mathematical Aspects

As discuss earlier, this approach is intended in order to optimize the Ip, A and B parameters to achieve an optimal operating time via the improvement of inverse-time characteristics. This process is carried on user-defined DOCRs. The final aim, which is denoted in (2) and some references such as [5, 10, 12, 21, 23, 30], is to minimize the overall DOCRs operating time under the situations of coordination constraints. Therefore, the objective function is:

$$Minimize\ \ T = \sum_{f=1}^{F}\left(\sum_{i=1}^{N} t_{i,f}^{P} + \sum_{k=1}^{N} t_{k,f}^{B}\right) \quad \forall i,k,f \tag{2}$$

The operating time of the primary and backup protection relays, is calculated refer to equation (3) [1, 3-33].

$$t_{i,k,f}^{P,B} = TDS \frac{A_{i,k}}{\left(\frac{I_{SCi,k,f}}{I_{Pi,k}}\right)^{B_{i,k}} - 1} \quad \forall i,k,f \tag{3}$$

As mentioned before, in this study, the TDS parameter for all relays are not optimized and capped the minimum range, determined as 0.1 s. The number of coordination constraints is related to the number of fault points and the backup relays for each main relay. To achieve a reliable and accurate protection strategy, the backup relay must not be operated before a specific time of the main relay, that is called CTI, given in (4) [1, 3-33]. It is usually between 0.2 s- 0.5 s and it is 0.3 s.

$$t_{k,f}^{B} - t_{i,f}^{P} \geq CTI \quad \forall i,k,f \tag{4}$$

The parameters of relay characteristics should be adjusted with their corresponding intervals. Hence, proper constraints are shown in Eqs. (5)- (7).

$$\max(I_{P\min}, I_{L\max}) \leq I_{Pi,k} \leq \min(I_{P\max}, I_{SC\min}) \quad \forall i,k \tag{5}$$

$$A_{\min} \leq A_{i,k} \leq A_{\max} \quad \forall i,k \tag{6}$$

$$B_{\min} \leq B_{i,k} \leq B_{\max} \quad \forall i,k \tag{7}$$

The pickup current constraints, Eq. (5), relate to the network load current and short circuit level. To assure that the relay does not operate under the normal loading or the small amount of overloading, the minimum limit for Ip is 1.1 times more than the maximum load current. In addition, to guarantee that the relay is sensitive to the lowest fault current, the maximum limit for Ip is less than or equal to 2/3 times of the minimum fault current. Regarding the 6 and 7, the lowest limit for A and B are specified 0.14 and 0.02, respectively. Likewise, 80 and 2 are assigned as the upper bound of these parameters, respectively. Finally, to ascertain the security of the suggested protection strategy, the relays operating time has been determined. Therefore, the next constraint regards the minimum and maximum possible times, assigned by 0.1 s and 2.5 s, in Eq. (8).

$$t_{\min} \leq t_{i,f}^{P}, t_{k,f}^{B} \leq t_{\max} \quad \forall i,k,f \tag{8}$$

The main variables, optimized for the coordination problem in this study, are the Ip, A and B for both protection relays. The fault current is considered as a parameter within the optimization but both the DG location and size will change fault current levels. To specify the load and fault currents seen by each relay, before optimizing the relay settings, the load flow and the fault analyses are conducted [34].

3. HYBRID PSO-WOA ALGORITHM

It is clearly recognized that the recommended approach for the user-defined DOCRs declares a non-linear programming method tackled based on hybrid swarm-based PSO-WOA algorithm. As we know, the PSO algorithm [35] directs some particles to random personal positions with small probability to keep away from local minimums (exploration) and this may have some threat of moving away from the global minimum. Exploration means ability of algorithm to try out wide number of feasible solutions. The WOA algorithm [36] uses logarithmic spiral function to encircling prey during hunting, so it covers larger area in unsure search space. The position of particle that is accountable for detecting the optimal solution of the non-linear problem is changed with the position of the whale that is equal to the position of particle but extremely effective in moving the solution towards optimal one. Combining the exquisite exploration feature of WOA with the exploitation phase of PSO, provides the best feasible optimal solution for the problem, and also removes the local stagnancy or optima shown in (9). WOA conduct the particles faster toward optimal setting and decrease computational time. The encoded particle consists three position which are devoted to determine the best optimal solution for the Ip, A and B parameters for protection relays (42 and 84 parameters for first and second test system, respectively).

$$\begin{aligned} V_i^{t+1} &= wV_i^t + c_1 r_{1,i}(Whale - Pos_i^t - X_i^t) \\ &\quad + c_2 r_{2,i}(Gbest_i^t - X_i^t) \quad \forall i,t \end{aligned} \tag{9}$$

The inertia weight between (0.4- 0.9) and linearly decreases. $c_1 = c_2 = 2$, also $r_{1,i}$ and $r_{2,i}$ are between (0-1). The new position of the i-th particle will be update by (10). The flowchart of the proposed approach is shown in Fig. 3.

$$X_i^{t+1} = X_i^t + V_i^{t+1} \quad \forall i,t \tag{10}$$

4. NUMERICAL RESULTS AND DISCUSSION

The IEEE 8-bus and distribution portion of IEEE 30-bus test systems are considered assessing the usefulness of the proposed approach and to discuss its expected merits over the recent one. The MATLAB software is used to perform optimization. These systems are typical meshed networks which are appropriate for the same studies. The IEEE 8-bus test system, depicted in Fig. 4(a), contains 7 lines and 14 DOCRs. Detailed information of this system could be attained in [10, 12, 23]. Likewise, the distribution portion of IEEE30-bus test system is displayed in Fig. 4(b). This system is fed through three

132/33 kV 50 MVA transformers connected at buses 2,8, and 12, where the 33 kV distribution portion is equipped with 16 lines and 28 DOCRs [12, 30]. The detailed data could be attained in [37]. In figures, the fault points pointed by F, as present in Eq. (2).

4.1. Numerical Studies on IEEE 8-bus Test System

The goal of protection coordination on IEEE 8-bus test system is to achieve minimizing the total primary relays operating time. The best optimal result is in [23] and the total operation time of the primary relays is 4.431 s. The proposed user-defined strategy is applied to this system. Optimal settings and operation time of relays are reported in Tables 3 and 4. Regarding Table 4, it is easy to infer that the basic constraint which is governed by Eq. (4), is taken for all relays. For example, the primary relays R2 and R9 set in 0.1s for F2 and backups are operating very fast after the 0.3s. The overall operating time is determined as 1.9502 s, which is reduced 56% with respect to the best conventional one and represents the effectiveness of the founded approach.

Table 3. Optimal relays settings for IEEE 8-bus system using proposed strategy

Relay	I_P(p. u.)	A	B	Relay	I_P(p. u.)	A	B
1	2.5	2.0721	0.6665	8	2.5	79.9992	1.8952
2	2.5	79.9929	1.5897	9	2.5	19.3298	1.6494
3	2.5	79.9885	1.6944	10	2.5	64.5584	2
4	2.5	60.0534	2	11	2.5	65.306	2
5	2.4997	9.2126	1.6755	12	2.5	80	1.5816
6	2.5	79.9873	1.8079	13	2.4983	2.4204	0.7652
7	2.5	51.0103	1.5379	14	2.5	51.2016	1.5421

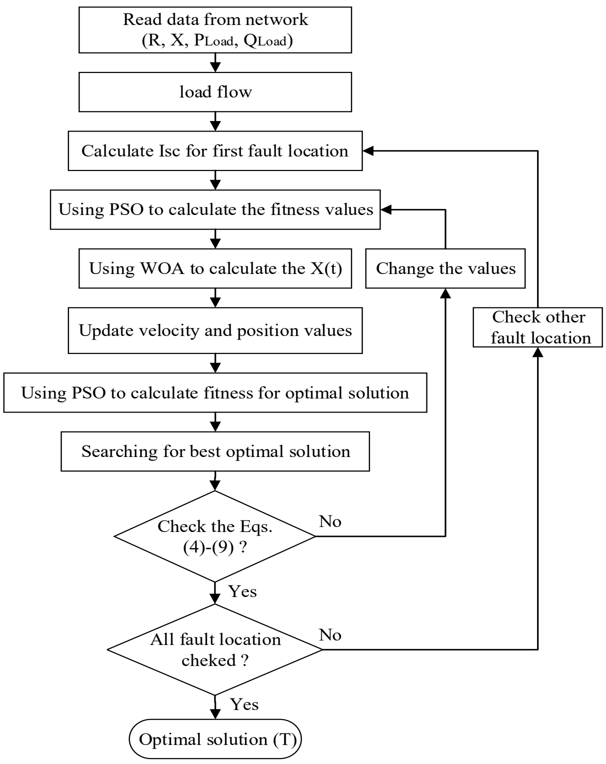


Fig. 3. Flowchart of the Combined PSO-WOA Algorithm for the Proposed Approach

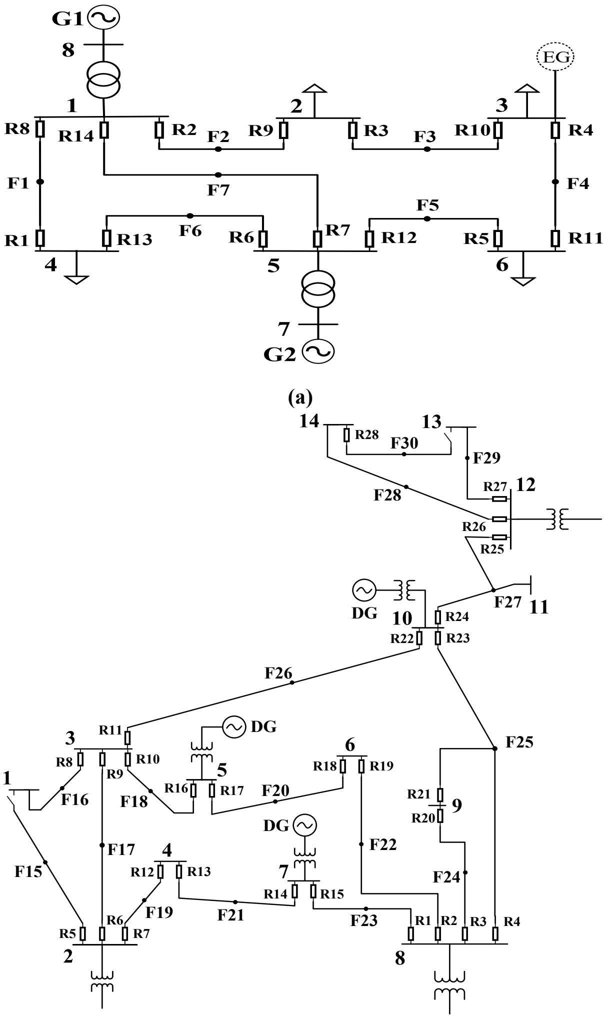


Fig. 4. Single Line Diagrams for (a) IEEE 8-bus and (b) the Distribution Portion of IEEE 30-bus Test Systems

Table 4. Optimal operating time of relays for IEEE 8-bus system using proposed strategy

Fault Point	Operation times in second (P: Primary, B: Backup)					
	P	B1	B2	P	B1	B2
F1	R1 0.1	R6 0.4	- -	R8 0.1001	R7 0.5156	R9 0.4001
F2	R2 0.2156	R1 0.5156	R7 0.5156	R9 0.1	R10 0.4	- -
F3	R3 0.2023	R2 0.5023	- -	R10 0.1579	R11 0.4579	- -
F4	R4 0.155	R3 0.455	- -	R11 0.1757	R12 0.4757	- -
F5	R5 0.1	R4 0.4	- -	R12 0.2213	R13 0.5213	R14 0.5213
F6	R6 0.1223	R5 0.4223	R14 0.5213	R13 0.1	R8 0.4	- -
F7	R7 0.1	R5 0.4223	R13 0.5213	R14 0.1	R1 0.5156	R9 0.4001

Table 5. Total operating time of primary relays for 8-bus system

Objective (s)	MILP [5]	SA-LP [10]	Dual Feasible [12]	Sine Cosine [23]	Proposed Strategy		
					PSO	WOA	PSO-WOA
$\sum t_{i,f}^{P}$	8.0061	8.4271	5.2233	4.431	2.1057	1.9843	1.9502
Overall Time	25.8563	27.5418	17.373	14.401	12.9583	11.745	11.2335

To provide more comparison between the proposed approach and the other optimizer method for this case, Table 5 shows the total primary relays operating time and Fig. 5 depicts the convergence operating time curve of IEEE 8-bus with three algorithms. As it can be inferred, by using the user-defined DOCRs considering the combined PSO-WOA algorithm, the higher decrease is achieved in the relays operating time. The population size, Iteration and number of running for the mentioned algorithms are selected as 100, 500 and 35, respectively.

4.2. Numerical Studies on the Distribution Portion of IEEE 30-bus Test System without DG

As the previous test system declares, the proposed OPC strategy is implemented to analyze the coordination process and to develop it as a valid solution. The obtained results of the conventional strategy are reported in [30] and the overall operation time is 64.1725 s. Optimal set-points for relays in proposed user-defined strategy are reflected in Tables 6. The relays operating time are given in Table 7. Regarding the results in Table 6, the primary relay R5 will have three settings; one setting for Ip equals to 0.0856 p.u. and two setting for inverse-time characteristics equals to A = 0.1439 and B = 0.0388. It can be observed that most of the primary relays have the minimum operating times, namely 0.1 s in Table 7 with no record of CTI miscoordination. To point out a useful illustration, specific faults and relays are analyzed based on the conventional and the user-defined strategy. In coordination approach [30], for F25 and F26, the R21 and R22 are selected as primary relays which is backed up by R25 (some of the primary and backup relays have not been considered). The primary relays are operating at 0.8243 s and 0.5230 s, respectively.

Table 6. Optimal relays settings for distribution portion of IEEE 30-bus system – without dg using proposed strategy

Relay	I_P(p.u.)	A	B	Relay	I_P(p.u.)	A	B
1	1.732	0.1426	0.2157	15	0.0721	0.1914	0.0204
2	1.2572	0.1417	0.296	16	0.0673	0.1756	0.02
3	1.6084	0.3189	0.4358	17	0.872	1.3008	1.9721
4	0.153	4.9019	0.8717	18	0.8354	1.7567	1.9268
5	0.0856	0.1439	0.0388	19	0.0774	10.0095	0.7753
6	0.2176	33.6781	1.1551	20	0.0827	0.254	0.02
7	0.9744	3.1273	1.5674	21	0.0184	6.1861	0.2234
8	0.02	0.1404	0.0273	22	0.0234	2.3767	0.1385
9	0.2176	25.3771	1.8595	23	0.0672	0.4087	0.02
10	1.1404	0.1407	0.2244	24	0.614	79.9703	1.3833
11	0.2564	1.5153	0.5135	25	0.07	79.9345	1.0787
12	0.2656	19.0601	1.9599	26	0.5603	1.8585	0.9977
13	0.9065	0.1499	0.3067	27	0.0749	0.1444	0.0413
14	0.9459	1.3216	1.0974	28	0.0449	0.1416	0.0457

Similarly, R25 are operating at 1.2548 s and 1.4906 s for the R21 and R22, respectively. For the same case in the proposed strategy by optimizing the Ip, A and B parameters, the primary relays in Table 7 are operating at 0.3467 s and 0.3128 s, respectively. The backup relay is tripping at 0.6468 s and 0.8460 s. The CTI value sets in minimum. Finally, the overall relays operating time based on the proposed strategy is obtained as 34.4041 s, which is decreased to 46.38% with respect to the conventional one.

Table 7. Optimal operating time of relays for distribution portion of IEEE 30-bus - without DG using proposed strategy

Fault Point	Operating times in second (P: Primary, B: Backup)				
	P	B1	B2	B3	B4
F15	R5	R9	R12	-	-
	0.1	0.4	0.5726	-	-
F16	R8	R6	R16	R22	-
	0.1	0.4305	0.4442	0.4358	-
F17	R6	R12	-	-	-
	0.1996	0.4996	-	-	-
	R9	R16	R22	-	-
	0.1	0.4	0.4	-	-
F18	R10	R6	R22	-	-
	0.1	0.4	0.44	-	-
	R16	R18	-	-	-
	0.3261	0.6261	-	-	-
F19	R7	R9	-	-	-
	0.1	0.5338	-	-	-
	R12	R14	-	-	-
	0.1	0.4	-	-	-
F20	R17	R10	-	-	-
	0.1	0.4	-	-	-
	R18	R2	-	-	-
	0.1	0.4	-	-	-
F21	R13	R7	-	-	-
	0.1	0.4	-	-	-
	R14	R1	-	-	-
	0.1	0.4	-	-	-
F22	R2	R15	R20	R21	R23
	0.1	0.7253	1.4515	0.8905	1.2848
	R19	R17	-	-	-
	0.163	0.463	-	-	-
F23	R1	R19	R20	R21	R23
	0.1	0.4522	0.7421	0.5957	0.8336
	R15	R13	-	-	-
	0.3496	0.6496	-	-	-
F24	R3	R15	R19	R21	R23
	0.1	0.4	0.4	0.4	0.7495
	R20	R4	R23	-	-
	0.4495	0.7495	0.7495	-	-
F25	R4	R15	R19	R20	-
	0.1	0.4266	0.5106	0.4	-
	R21	R3	R25	-	-
	0.3467	0.6468	0.6468	-	-
	R23	R11	-	-	-
	0.7075	1.0075	-	-	-
F26	R11	R6	R16	-	-
	0.1	0.5063	0.5606	-	-
	R22	R4	R21	R25	-
	0.3128	0.8755	0.6128	0.8460	-
F27	R24	R4	R11	R21	-
	0.1195	0.4981	0.4616	0.5594	-
	R25	-	-	-	-
	0.2822	-	-	-	-
F28	R26	R24	-	-	-
	0.1	0.5241	-	-	-
F29	R27	R24	-	-	-
	0.1	0.4	-	-	-
F30	R28	R26	-	-	-
	0.1	0.4	-	-	-

4.2. Numerical Studies on the Distribution Portion of IEEE 30-bus Test System with DG

To assess the efficiency of the proposed OPC strategy, three synchronous-based DG (SBDG) rated at 5 MVA which are operated at unity power factor with 9.67% transient reactance, feed the distribution portion of IEEE 30-bus system via a 480 V/33 kV step-up transformer with 5% transient reactance at buses 5, 7 and 10 [12, 30]. When the SBDGs are added, the fault currents seen by the relays can be changed. If the same user-defined settings, which are reported in Table 6, are used, it leads to many cases of primary relays operating time and backup/primary relay coordination are becomes less than 0.1 s and 0.3 s, respectively, as shown in Table 8. Moreover, some other cases have the CTI under 0.2 s, like R5- R9 for F15, but some cases could be considered as the coordinated pairs such as R8-R6, R8-R22 for F16 and R9-R22 for F17 in Table 8.

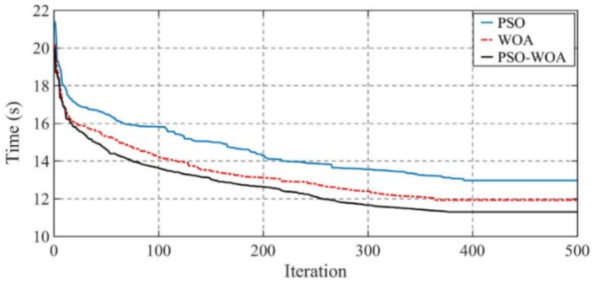


Fig. 5. The convergence operating time curves of IEEE 8-bus system

Table 8. Sample of operating time of relays for distribution portion of IEEE 30-bus system- with DG using the basic settings

Fault Point	Operating times in second (P: Primary, B: Backup)				CTI
	P	B1	B2	B3	
F15	R5	R9	R12	-	0.1833, -0.0216
	0.0932	0.2765	0.0714	-	
F16	R8	R6	R16	R22	0.3319, 0.2916, 0.3223
	0.1	0.4319	0.3916	0.4223	
F17	R6	R12	-	-	
	0.1908	0.298	-	-	0.1072
	R9	R16	R22	-	
	0.0685	0.3541	0.3847	-	0.2856, 0.3162

Table 9. Optimal relays settings for distribution portion of IEEE 30-bus system- with DG using proposed strategy

Relay	I_P(p.u.)	A	B	Relay	I_P(p.u.)	A	B
1	1.7496	0.1408	0.1973	15	0.0552	0.2389	0.0202
2	1.3154	0.3003	0.5589	16	0.0539	0.2204	0.0203
3	1.614	3.3163	1.9756	17	1.0767	0.1433	0.3158
4	0.2156	0.3266	0.1577	18	0.8863	0.2034	0.3531
5	0.078	0.14	0.0363	19	0.0802	77.1113	1.608
6	0.1958	52.5114	1.281	20	0.0752	0.2704	0.02
7	0.9141	6.0567	1.9085	21	0.0168	0.4908	0.0263
8	0.0184	0.1417	0.0268	22	0.0198	38.1968	0.6472
9	0.1824	54.1883	1.8799	23	0.0534	0.4758	0.0202
10	1.1391	0.1855	0.2678	24	0.064	79.8245	1.3708
11	0.2887	0.1419	0.0758	25	0.055	72.6284	0.95
12	0.3637	13.7223	1.9998	26	0.5764	0.1488	0.8824
13	0.9373	0.1741	0.3504	27	0.0715	0.1404	0.0421
14	0.8747	6.1173	1.9862	28	0.0416	0.1402	0.0439

Accordingly, it's essential to compute new optimal settings for this network. The optimal results using the conventional strategy are in [30] and the total operating time is 63.27 s. The recommended approach considering three optimal settings with the accessibility of defining the new inverse-time characteristics of each relay. New optimal set-point results are reflected in Table 9. These new settings demonstrate the fast-response relay operation against the different fault currents. Table 10 presents the optimal primary and backup relay operating times. It is recognized that the basic constraint, illustrated by Eq. (4), is assured between pair relays.

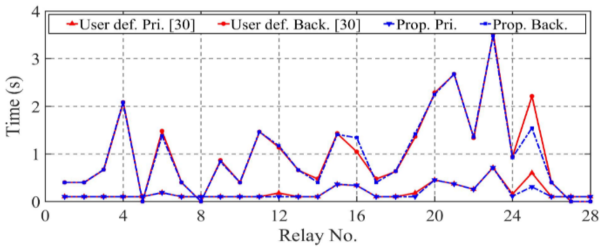
Table 10. Optimal operating time of relays for distribution portion of IEEE 30-bus- with DG using proposed strategy

Fault Point	Operating times in second (P: Primary, B: Backup)				
	P	B1	B2	B3	B4
F15	R5	R9	R12	-	-
	0.1	0.4	0.6854	-	-
F16	R8	R6	R16	R22	-
	0.1	0.4464	0.4381	0.479	-
F17	R6	R12	-	-	-
	0.1851	0.4851	-	-	-
	R9	R16	R22	-	-
	0.1	0.4	0.4	-	-
F18	R10	R6	R22	-	-
	0.1	0.4	0.4737	-	-
	R16	R18	-	-	-
	0.3371	0.6371	-	-	-
F19	R7	R9	-	-	-
	0.1	0.4341	-	-	-
	R12	R14	-	-	-
	0.1	0.4	-	-	-
F20	R17	R10	-	-	-
	0.1	0.4	-	-	-
	R18	R2	-	-	-
	0.1	0.4	-	-	-
F21	R13	R7	-	-	-
	0.1	0.4	-	-	-
	R14	R1	-	-	-
	0.1	0.4	-	-	-
F22	R2	R15	R20	R21	R23
	0.1	0.5877	1.1699	0.6809	1.1602
	R19	R17	-	-	-
	0.1	0.4	-	-	-
F23	R1	R19	R20	R21	R23
	0.1	0.4663	0.6791	0.516	0.8179
	R15	R13	-	-	-
	0.36	0.66	-	-	-
F24	R3	R15	R19	R21	R23
	0.1	0.4	0.4	0.4	0.7501
	R20	R4	R23	-	-
	0.4501	0.7501	0.7501	-	-
F25	R4	R15	R19	R20	-
	0.1	0.4199	0.5532	0.4	-
	R21	R3	R25	-	-
	0.3668	0.6668	0.6668	-	-
	R23	R11	-	-	-
	0.7106	1.0107	-	-	-
F26	R11	R6	R16	-	-
	0.1	0.534	0.4997	-	-
	R22	R4	R21	R25	-
	0.2556	0.8544	0.5556	0.8758	-
F27	R24	R4	R11	R21	-
	0.1155	0.4773	0.4516	0.5246	-
	R25	-	-	-	-
	0.3064	-	-	-	-
F28	R26	R24	-	-	-
	0.1	0.5241	-	-	-
F29	R27	R24	-	-	-
	0.1	0.4	-	-	-
F30	R28	R26	-	-	-
	0.1	0.4	-	-	-

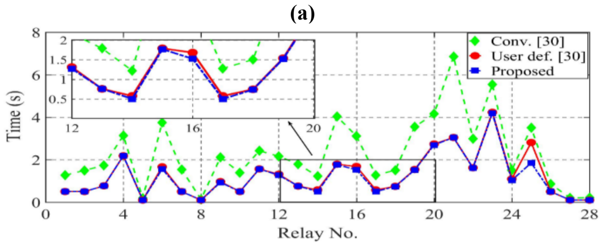
For example, in Table 10 for F21, operating time of R13 and R14 experiences 0.1 s. If the primary relays lose to operate, the backup relays R7, R1 will operate after 0.4 s, knowing the CTI = 0.3 s. The maximum total time reduction is for R25. So, that in user-defined strategy [30] it equals to 2.8105 s, but in proposed strategy it is 1.849 s. The overall relays operating time is 33.0659 s and lead to 47.74% reduction compared with the conventional strategy. The overall operating time of these cases are reported in Table 11 with three various optimization algorithms to confirm the efficiency of the proposed strategy in obtaining optimal solutions. Graphically, Fig. 6(a) depicts the differences between primary and backup relays operating time based on the suggested and other approaches for midpoint faults, and Fig. 6(b) demonstrates the comparison of overall relays operating times. Regarding these figures, simply it and be determined that in the coordination process, the proposed PC strategy significantly decreases the operating time versus the other recent approaches.

Table 11. Overall relays operating time (s) with different algorithms

Dist. Net. Top.	Conv. [30]	User-defined SQP[30]	GWO [21]	Dual Feasible [23]	Proposed Strategy		
					PSO	WOA	PSO-WOA
No DG	64.1725	35.0625	34.588	34.45	35.4783	34.9524	34.4041
On DG	63.27	34.5565	34.172	34.06	34.1067	33.5725	33.0659



(a)



(b)

Fig. 6. The performance of the suggested versus other approach in midpoint fault (a) the discrimination time for primary and backup DOCRs, and (b) the overall relays operating time

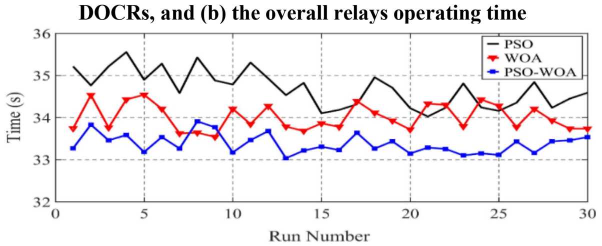


Fig. 7. Variation of the best overall relays operating time obtained for distribution portion of IEEE 30-bus system - with DG

4.3. Evaluating Various SBDG Location and Size on Distribution Portion of IEEE 30-bus Test System

To further assess the efficiency and performance of the suggested protection strategy, different SBDG units regarding location and size are integrated in distribution portion of IEEE 30-bus test system. This can cause the line currents are changed, also the fault currents are remarkable increase in some part of network which results in the failure of directional protection coordination. To evaluate the application of the recommended approach compared to other recent, different SBDGs integration and the total relay operating time are explained in Table 12. The obtained results prove the proposed approach is very efficient in the relay parameters adjustment to any kinds of integration. Moreover, it significantly reduces the total relay operating time versus other methods. This issue demonstrates the technical and mathematical efficiency of the new proposed approach discussed in section 2. 1.

Table 12. Comparing the overall relays operating time considering different integrations

DG integration plan		Conventional [30]	User-defined SQP [30]	Proposed Strategy
Bus No.	Size (MVA)			
-	-	64.1725 s	35.0625 s	34.4041 s
3	2	64.0842 s	34.9774 s	34.3073 s
3	4	64.0014 s	34.4828 s	33.8115 s
3	6	63.9232 s	34.7954 s	34.1236 s
6	2	64.3032 s	35.5473 s	34.8663 s
6	4	64.4239 s	35.0789 s	34.3865 s
6	6	64.5316 s	35.0992 s	34.4184 s
3, 6	2	64.2459 s	34.9251 s	34.2115 s
3, 6	4	64.2374 s	34.8374 s	34.1027 s
3, 6	6	64.2115 s	34.8573 s	34.1205 s
3, 6, 10	2	63.581 s	34.5639 s	33.8132 s
3, 6, 10	4	63.1246 s	34.3148 s	33.5081 s
3, 6, 10	6	62.7497 s	34.1355 s	33.3214 s

Table 13. Evaluating the impact of fault resistance on overall relays operating time

R_{fault} (Ω)	Conventional [30]	Proposed Strategy
0	63.27 s	33.0659 s
0.01	63.2734 s	33.0678 s
0.05	63.2763 s	33.0695 s
0.1	63.2795 s	33.0712 s
0.2	63.2842 s	33.0737 s
0.5	63.2874 s	33.0763 s

4.2. Assessing the impacts of fault resistance on IEEE 30-bus test system.

In addition to the bolted three-phase faults, the mentioned strategy considers the faults with various resistance values in the same SBDG size at buses 5, 7, 10. Several cases of this issue are simulated and outcomes are in Table 13. The results again confirm the efficiency and performance of mentioned approach compared to recent ones.

4.3. Results Validation

As discussed before, a consecutive optimization method based on hybrid PSO-WOA algorithm is used in optimization flow. Three different optimization algorithms are tested to certify the efficiency of the suggested approach, shown in Fig. 7. Clearly, near-optimal solution is achieved for protection coordination problem, and the performance of the novel approach is confirmed.

5. CONCLUSIONS

This paper presents a new OPC strategy for numerical DOCRs using a truth table based on the mathematical aspects in meshed distribution networks with and without SBDGs. Hence, the proposed approach is modeled with reducing the total relays operating time as the objective function in coordination tasks subjected to the technical constraints such as the pickup current (Ip), relay characteristics (A), inverse-time type (B), and coordination time interval inequality. As a novelty, there are simultaneously considered Ip, A and B as optimization variables which increases the search space for coordination alternatives, enhancing the OPC performance. Due to the fact that the formulation of optimization problem is non-linear, this paper develops two different optimization algorithms namely PSO, WOA and hybrid PSO-WOA to attain a proper and optimal solution. Furthermore, the proposed approach can be used to obtain a coordination with multiple parameters for each operational mode. The IEEE 8-bus and distribution portion of the IEEE 30-bus test system were carried out to evaluate the applicability of proposed approach. Through the results, the following contributions were mentioned as the main findings of this research:

- A new method was presented to optimize the variable parameters of numerical DOCRs with a truth table based on the mathematical aspects.
- An efficient user-defined setting was established to attain the optimal adjustments for the numerical DOCRs.
- Contrary to the conventional strategy, the overall relays operation times were significantly reduced through the proposed approach, and a fast-response fault clearance strategy was provided while keeping the CTI of pair relays in minimum.

Moreover, the suggested approach was presented to fulfill the coordination necessities in remarkable penetration of SBDGs. The SBDG location and size were precisely investigated. A similar point was noticed for the faults with various resistance values. It is essential to note that the conducted research is still an open and ongoing issue. Thus, the authors are on extending a mixed protection strategy by using the user-defined and dual setting DOCRs.

REFERENCES

[1] A. G. Phkdke, and J. S. Throp, Computer relaying for power systems, John Wiley & Sons, 2009.

[2] G. Derakhshan, H. Shahsavari and A. Safari, "co-evolutionary multi-swarm PSO based optimal placement of miscellaneous DGS in a real electricity grids regarding uncertainties," *J. Oper. Autom. Power Eng.*, vol. 10, no. 1, pp. 71-79. 2022.

[3] A. S. Noghabi, H. R. Mashhadi, and J. Sadeh, "Optimal coordination of directional overcurrent relays considering different network topologies using interval linear programming", *IEEE Trans. Pow. Del.*, vol. 25, pp. 1348-54, 2010.

[4] S. T. P. Srinivas and K. Shanti-Swarup, "A New mixed integer linear programming formulation for protection relay coordination using disjunctive inequalities", *IEEE Pow. Energy Tech. Sys. J.*, vol. 6, pp. 104-112. 2019.

[5] N. Banerjee, R. Narayanasamy, and O. Swathika, "Optimal coordination of overcurrent relays using two phase simplex method and particle swarm optimization algorithm", *Int. Conf. Pow. Emb. Drive Cont.*, 2017.

[6] P. K. Choudhary and D. K. Das, "Optimal coordination of over-current relay in a power distribution network using opposition based learning fractional order class topper optimization (OBL-FOCTO) algorithm", *App. Soft Comp.*, vol. 113, p. 107916. 2021.

[7] T. Khurshaid et al., "Modified particle swarm optimizer as optimization of time dial settings for coordination of directional overcurrent relay", *J. Elec. Eng. & Tech.*, vol. 14, no. 1, pp. 55-68. 2019.

[8] P. Alaee and T. Amraee, "Optimal coordination of directional overcurrent relays in meshed active distribution network using imperialistic competition algorithm", *J. Modern Pow. Sys. Clean Energy*, vol. 9, no. 2, pp. 416-422. 2021.

[9] A. Draz, M. M. Elkholy and A. A. El-Fergany, "Slime mould algorithm constrained by the relay operating time for optimal coordination of directional overcurrent relays using multiple standardized tripping curves", *Neural Comput. & Applic.*, vol.33, pp. 11875-11887. 2021.

[10] A. A. Kida, A. E. L. Rivas and L. A. Gallego, "An improved simulated annealing–linear programming hybrid algorithm applied to the optimal coordination of directional overcurrent relays", *Elec. Pow. Sys. Res.*, vol. 181, pp. 106197. 2020.

[11] P. Omidi, S. Abazari and S. M. Madani, "Optimal coordination of directional overcurrent relays for microgrids using hybrid interval linear programming - differential evolution", *J. Oper. Autom. Power Eng.*, vol. 10, No. 2, pp. 122-133. 2022.

[12] A. Darabi, M. Bagheri, and G.B. Gharehpetian, "Dual feasible direction-finding nonlinear programming combined with metaheuristic approaches for exact overcurrent relay coordination", *Int. J. Elec. Power & Energy Systems*, vol. 114, pp. 105420. 2020.

[13] S. K. ElSayed and E.E. Elattar, "Hybrid harris hawks optimization with sequential quadratic programming for optimal coordination of directional overcurrent relays incorporating distributed generation", *Alex. Eng. J.*, vol, 60. No. 2, pp. 2421-2433. 2021.

[14] C. H. Kim et al., "Gray wolf optimizer for the optimal coordination of directional overcurrent relay", *J. Elec. Eng. & Tech.*, vol. 13, no. 3, pp. 1043-1051. 2018.

[15] S. Ghobadpour, M. Gandomkar and J. Nikoukar, "Multi-objective function optimization for locating and sizing of distributed generation sources in radial distribution

networks with fuse and recloser protection," *J. Oper. Autom. Power Eng.*, vol. 9, no. 3, pp. 266-273. 2021.
[16] SIEMENS, Numerical Overcurrent Protection Relay 7SJ82/7SJ85, Available: http://www.siemens.com
[17] AREVA, Directional/Non-Directional Overcurrent Protection Relay, Available: http://www.mt.schneider-electric.be
[18] L. Hong et al., "User-defined dual setting directional overcurrent relays with hybrid time current-voltage characteristics-based protection coordination for active distribution network", *IEEE Access*, vol. 9, pp. 62752-69, 2021.
[19] A. E. C. Momesso, W.M. S. Bernardes and E. N. Asada, "Fuzzy adaptive setting for time-current-voltage based overcurrent relays in distribution systems", *Int. J. Elec. Power & Energy Systems*, vol. 108, pp. 135-144. 2019.
[20] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Optimal coordination of directional overcurrent relays using a new time-current-voltage characteristic", *IEEE Trans. on Po. Del.*, vol. 30, no. 2, pp. 537-544. 2015.
[21] S. Dadfar and M. Gandomkar, "Augmenting protection coordination index in interconnected distribution electrical grids: Optimal dual characteristic using numerical relays", *Int. J. Elec. Power & Energy Systems*, vol. 131, p. 107107. 2021.
[22] A. Yazdaninejadi, M. S. Naderi, G. B. Gharehpetian, and V. Talavat, "Protection coordination of directional overcurrent relays: New time current characteristic and objective function", *IET Gen., Trans. & Dist.*, vol. 12, no 1, pp. 190-199. 2018.
[23] K. Sarwagya, P. Nayak and S. Ranjan, "Optimal coordination of directional overcurrent relays in complex distribution networks using sine cosine algorithm", *Elec. Pow. Sys. Res.*, vol. 187, pp. 106435, 2020.
[24] A. Tjahjono et al., "Adaptive modified Firefly algorithm for optimal coordination of overcurrent relay", *IET Gen., Trans. & Dist.*, vol. 11, no. 10, pp. 2575-2585. 2017.
[25] A. Darabi, M. Bagherib, and G.B. Gharehpetiana, "Highly reliable overcurrent protection scheme for highly meshed power systems", *Int. J. Elec. Power & Energy Systems*, vol. 109, pp. 105874. 2020.
[26] C. A. Castillo, A. Conde, and M. Y. Shihc, "Improvement of non-standardized directional overcurrent relay coordination by invasive weed optimization", *Elec. Pow. Sys. Res.*, vol. 157, pp. 48-58. 2018.
[27] H. R. E. H. Bouchekara, M. Zellagui, M. A. Abido, "Optimal coordination of directional overcurrent relays using a modified electromagnetic field optimization algorithm", *App. Soft Comp.*, vol. 54, pp. 267-283. 2017.
[28] S.M. Saad, N. El-Naily, and F.A. Mohamed, "A new constraint considering maximum PSM of industrial over-current relays to enhance the performance of the optimization techniques for microgrid protection schemes", *Sustain. Cities Soc.*, vol. 44, pp. 445-57. 2019.
[29] A. Chawla, B. R. Bhalja, B. K. Panigrahi, and M. Singh, "Gravitational search based algorithm for optimal coordination of directional overcurrent relays using user defined characteristic", *Elect. Pow. Comp. Syst.*, vol. 46, no. 1, pp. 43-55. 2018.
[30] H. M. Sharaf, H. H. Zeineldin, D. K. Ibrahim, and E. E. A. El-Zahab, "A proposed coordination strategy for meshed distribution system with DG considering user-defined characteristics of directional inverse time overcurrent relays", *Int. J. Elec. Power & Energy Systems*, vol. 65, pp. 49-58. 2015.
[31] E. Naderi, A. Dejamkhooy, S.J. Seyedshenava and H. Shayeghi, "MILP based optimal design of hybrid microgrid by considering statistical wind estimation and demand response," *J. Oper. Autom. Power Eng.*, vol. 10, no. 1, pp. 54-65. 2022.
[32] S. A. Ahmadi et al., "Application of hyper-spherical search algorithm for optimal coordination of overcurrent relays considering different relay characteristics", *Int. J. Elec. Power & Energy Systems*, vol. 83, pp. 443-449. 2016.
[33] M. El-kordy, A. El-fergany and A. F. A. Gawad, "Various Metaheuristic-Based Algorithms for Optimal Relay Coordination: Review and Prospective", *Arch. Comput. Methods Eng.*, vol. 28, pp. 3621-3629. 2021.
[34] H. Saadat, Power System Analysis. McGraw-Hill, 2009.
[35] J. Kennedy and R. Eberhart, "Particle swarm optimization", *Int. Conf. on Neur. Net.*, pp. 1942–1948. 1995.
[36] S. A. Mirjalili and A. Lewis, "The whale optimization algorithm", *Adv. in Eng. Soft.*, vol. 95, pp. 51–67. 2016.
[37] Univ. Washington. Seattle, Mar. 2006, Available: http://www.ee.washington.edu/research/pstca/