Research paper

New Distance Protection Framework in Sub-Transmission Systems through an Innovative User-defined Approach

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Article Info	Abstract
  *Corresponding Author's Email Address: a.yazdaninejadi@sru.ac.ir	**Background and Objectives:** Protection of sub-transmission systems requires maintaining selectivity in the combinatorial scheme of distance and directional overcurrent relay (DOCR). This presents a complex challenge that renders the need for a robust solution. Thereby, the objective of the present study is to decrease the number of violations and minimize the tripping time of relays in this particular issue. **Methods:** This study deals with this challenge by using numerical DOCRs which follow non-standard tripping characteristics without compromising the compatibility of the curves. In this process, the time-current characteristics of relays are described in such a manner that they can maintain selectivity among themselves and with distance relays. Therefore, in addition to the second zone timing of distance relays, time dial settings (TDS), and plug settings of overcurrent relays, the other coefficients of the inverse-time characteristics are also optimized. The optimization procedure is formulated as a nonlinear programming model and tackled using the particle swarm optimization (PSO) algorithm. **Results:** This approach is verified by applying on two test systems and compared against conventional methods. The obtained results show that the proposed approach helps to yield selective protection scheme owing to the provided flexibility. **Conclusion:** The research effectively enhanced selectivity in sub-transmission systems and minimizing relay tripping times through the innovative use of numerical DOCRs and PSO-based optimization.

Introduction

Clearing power grids faults selectivity yields a safe and reliable protection scheme. Due to the low cost and simplicity in implementation of DOCRs, deploying these relays besides distance relays is so prevalent in sub-transmission systems [1]-[4]. In order to achieve selective protection in such systems, it is necessary to fulfill three different coordination scenarios that involve: (1) a distance relay with a distance relay, (2) a DOCR with another DOCR, and (3) a DOCR with a distance relay. All of the above needs to be achieved within minimal relay tripping time. Numerous efforts have been made to address the issue of optimal solutions for relay coordination problems. Linear programming techniques such as simplex, and dual simplex are explored in [5], [6]. Requiring initial guesses based on user intuition is pointed in literatures as the drawback of these techniques [7] which may lead them towards local minima. Relays protection coordination is also formulated to tackle by heuristic optimization machines in [7]-[10]. In [10] group searching optimization is improved to solve the DOCRs coordination problem by enhancing its searching ability. Some other innovative approaches are proposed in [11]-

[15]. Aforementioned references have been concentrated on solving overcurrent relaying, and less work has been dedicated to solve the combinatorial coordination challenge. In [16], [17], as initial studies, the coordination of DOCRs beside distance relays is investigated by linear programing-based techniques. The main facing problems of these studies are first, the same tripping times are considered for second zone of all distance relays and second, there are some records of violations in selectivity constraints. In [7]-[18] the authors enhanced the coordination quality and reduced the total tripping time of relays by adjusting the second zone timing of distance relays and utilizing intelligence-based optimization techniques.

However, violation among selectivity constraints is still present between several pair relays. Another key point is the overcurrent relays are not coordinated in far-end point faults which may lead mal-operations in clearing faults along the protected lines.

Thanks to the advances in intelligent electronic devices (IEDs), numerical relays [19]-[22] are evolved as competent alternatives to overcome the existing hurdles of the conventional relays. These relays are recently commercialized by some manufacturers [23], [24] which are benefitting from a mature design and simple implementation. Users can easily preset these relays, allowing for the inclusion of arbitrary functionalities through software applications as needed. In [25], numerical DOCRs are employed to protect a radial distribution network. Piece-wised linear time-current characteristics are presented for DOCRs. In [26], based on numerical DOCRs, a new scheme is devised for protecting interconnected distribution networks in order to achieve lower tripping times for clearing probable faults. In [27], non-standard tripping characteristics are employed to coordinate dual-setting DOCRs. The need for communication links is the main drawback of deploying dual-setting DOCRs. In [28], different characteristics are provided for DOCRs to eliminate violations in combinatorial scheme of D&DOCRs. However, this method restricts the optimization space due to the limited number of characteristics available. In [29], based on numerical distance relays, non-standard tripping characteristics are considered for distance relays. However, presence of violations is still a challenging task. Although there is an enhancement in the quality of coordination metrics in abovementioned references, the presented approaches can be further extended.

As mentioned earlier, numerical relays allow users to implement arbitrary time-current characteristics through the optimized parameters. Such issues are not dealt in the preceding approach to alleviate violations in coordination problems. Thus, a non-standard coordination process is devised for coordinating DOCRs and distance relays with the aim of minimizing the number of violations and the total tripping time of relays. During the proposed process, overcurrent relaying is performed for far-end points. Therefore, an efficient coordination scheme is adopted, characterized by the following main features:

- A non-standard coordination process is proposed, optimizing the relays' characteristics intuitively within a combinatorial protection scheme;
- The Number of violations can be reduced sensibly;
- The proposed approach reduces the total tripping time of relays considering both the primary and backup relays;
- Discrimination times of relays are also sensibly diminished.

The established non-standard process for coordinating DOCRs and distance relays reveals a nonlinear optimization model. In this study, the model is addressed using PSO.

The ongoing study proceeds as follows: The proposed non-standard coordination process, which incorporates numerical DOCRs alongside distance relays, is explained in Section 2. Subsequently, it is formulated in section 3. The results of the investigated cases are discussed in section 4. The last section concludes the remarks.

The Proposed Scheme of D&DOCRs

A. Combinatorial Protection Scheme of D&DOCRs

As noted, combinatorial scheme of distance relays and DOCRs are commonly used for the protection of sub-transmission networks. The fundamental concept of this protection scheme is illustrated in Fig. 1. This scheme accommodates varying numbers of relays and relay pairs. Referring to Fig. 1, the number of relays is duplicated. In addition, instead of each relays pair, there are four pairs of relays. For the sake of clarity, consider a fault at point *F*. In this case, if the conventional scheme is adopted, R_p^{Dis} typifies primary relay which is backed up with R_b^{Dis}. This is while, in the wake of employing combinatorial scheme, ($R_p^{Dis} : R_b^{Dis}$), ($R_p^{Dis} : R_b^{OC}$), ($R_p^{OC} : R_b^{Dis}$), and ($R_p^{OC} : R_b^{OC}$) are pairs of relays. R_p^{OC} and R_b^{OC} identify primary and backup DOCRs. For such schemes, the optimal settings of relays are perused with goals of selective, fast and sensitive operation of relays during faults. With this in mind, relays must be coordinated optimally and accurately. In this way, coordination process of proposed approach has two separate parts. Initially, the impedance settings for specifying the three different zones of distance relays are calculated. Subsequently, the time settings for the second zone of distance relays *(T_{Z2})* as well as the settings for DOCRs, are optimally determined.
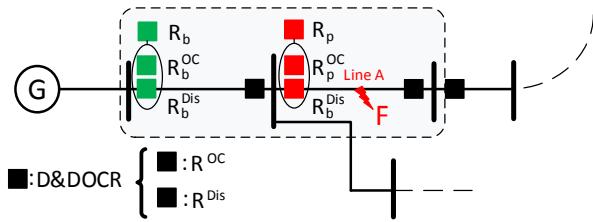
Fig. 1: Simple portion of sub-transmission network.

The impedance settings of distance relays must be calculated before initiating the optimization process. Distance relays feature different protection zones (typically three) to enable selective and sensitive operation. At least three protection zones are considered for distance relays. As shown in Fig. 2, The Z_1 is utilized for protecting the first zone of primary line. It is configured to detect probable faults on 80% of the primary line without introducing any intentional time delay. Generally, Z_2 is the second zone and it is set to cover 120% of the primary line impedance, providing a sufficient margin to accommodate potential errors in relaying. Additionally, the second protection zone acts as a backup for a portion of the adjacent lines with Z_2. The setting of the Z_3 which is the third zone, encompasses the primary protected line and the longest line from the remote bus. Conventionally, coordination between Z_2 and Z_3, and with the Z_1, is achieved through delayed trip outputs (by 15–30 cycles for Z_1 and approximately 20 cycles for Z_3.)
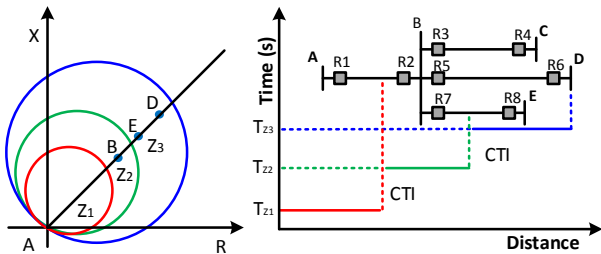

Fig. 2: Illustration of different zones of distance relay.

After specifying the zones of distance relays, T_{Z2} of distance relays must be coordinated with DOCRs. This means that the pairs of relays must satisfy selectivity constraints at five critical points, as depicted in Fig. 3. In essence, at these five critical points, backup relays must initiate operation after the primary relays in a timely fashion, adhering to the critical time interval (CTI), meaning they must operate at least CTI seconds after the primary relays. This ensures selectivity at other points along the line. CTI is defined as the minimum time gap between the tripping times of primary relays and those of their backups. The critical points are identified as follows: F_1 is the first critical point, and it is near the end of the primary line, F_2 is the second critical point and it is at the

end of the second zone of the backup distance relay (Z_{2b}), F_3, which is the third critical point, is at the beginning of the second zone of the primary distance relay (Z_{2p}), F_4 is the fourth critical point, and it is at the far-end side of the primary line, and F_5 is the fifth critical point and it is at the beginning of the first zone of the primary distance relay. To prevent curve crossing, in addition to F_1, DOCRs must also be coordinated at F_4, as outlined in Fig. 3(a). Similarly, to fulfill the coordination requirement between R_b^{Dis} and R_p^{OC}, it is necessary to meet the CTI at F_2, as shown in Fig. 3(b). Likewise, to satisfy the coordination task between R_p^{OC} and R_b^{Dis}, meeting the CTI at F_3 and F_5 is crucial, as demonstrated in Fig. 3(c). Under these conditions, all relays will be coordinated along the protected lines.
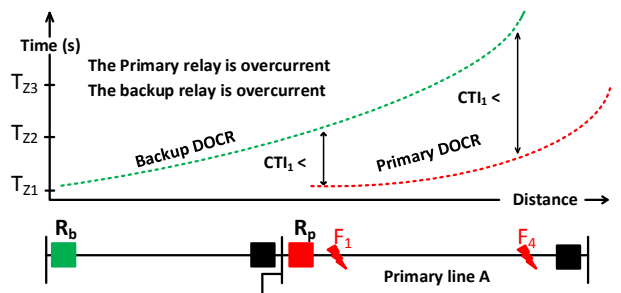
(a)
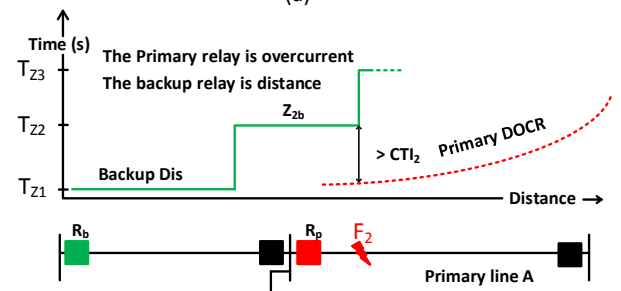
(b)
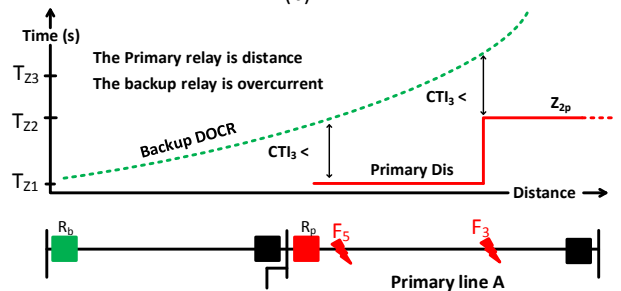
(c)

Fig. 3: Five critical points in coordination process

B. Proposed Coordination Process Based on Arbitrary Characteristics

According to IEC/IEEE/AREVA, relay operating times are derived from their characteristic curves as follows:

$$t = TDS\left(\frac{A}{\left(\frac{I_F}{I_p}\right)^B - 1} + C\right) \quad (1)$$

where I_p is the pickup current of relay. In practice, I_p is bigger than the maximum load current passing through the relay by same degree. This will guarantee the stability of the relay under normal loading condition of the network. Moreover, I_F is the magnitude of fault current which is seen by the relay. A, B and C are constant and depend on relays time-current characteristics. Typically, they are chosen from Table 1. For instance, standard-inverse (SI), very-inverse (VI), and extremely-inverse (EI) characteristics are depicted in Fig. 4. In the conventional coordination method, *TDS*, I_p, and I_F are adjustable, while other parameters are considered constant. In contrast, commercial numeric DOCRs offer the ability to set up arbitrary time-current characteristics in tabular form, graphically [25], and by adjusting certain constant coefficients of the relay operation function [16]. For instance, an arbitrary characteristic is displayed alongside standard characteristics in Fig 4.

Table 1: The arrangement of channels

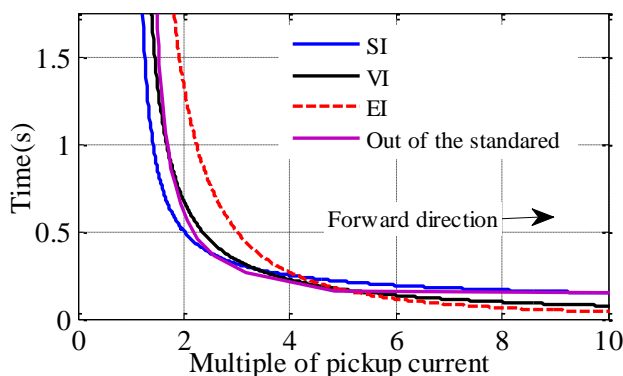| Characteristic No.	Type of characteristic	A factor	B factor	C factor
1	Short Time Inverse	0.05	0.04	0
2	Standard Inverse	0.14	0.02	0
3	Very Inverse	13.5	1	0
4	Extremely Inverse	80	2	0
5	Long Time Inverse	120	1	0
6	Moderately Inverse	0.0515	0.02	0.114
7	Very Inverse	19.61	2	0.491
8	Extremely Inverse	28.2	2	0.1217

Fig. 4: An example of out of standard time-current curve.

This feature relaxes some constraints in coordination problem and enhances relaying flexibility and extensibility. Hence, in the proposed coordination process, besides *TDS*, I_p, and T_{Z2}, the constant coefficients

of DOCRs, A and B are also considered as optimization variables. To put it differently, in conventional protection schemes, only one standard time-current characteristic, typically SI, is used for all DOCRs. This is while, thanks to advances in numerical relays, the proposed coordination process allows for the provision of an optimal characteristic for each DOCR. Therefore, time-current characteristic of overcurrent relays and second zone timing of distance relays are not the same for all relays. Furthermore, each overcurrent relay's characteristic is designed optimally. The explained coordination process is shown in the flowchart of Fig. 5. It is crucial to consider the effects of in-feed and out-feed in the coordination process of the combinatorial scheme.
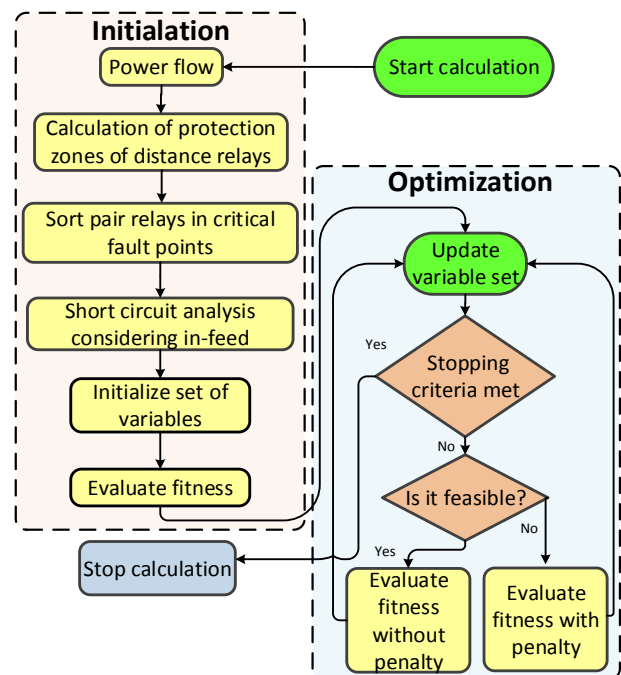

Fig. 5: Flowchart of proposed coordination process.

Problem Formulation

This paper aims to determine the values of *TDS*, I_p, A, and B for DOCRs and T_{Z2} of distance relays optimally. This is done to minimize the number of violations and the total tripping time of the relays. Consequently, the objective function that requires minimization is defined as follows.

$$F^{operating-time} : Minimize \ T = \sum_{f \in F}\left(\sum_{i \in I} t_p^{i,f} + \sum_{s \in S} t_b^{i,f,s}\right) \quad (2)$$

where t_p is tripping time of primary relay and t_b is tripping time of backup relay. Furthermore, *f*, *i*, and *s* are the indices of fault points, all relays, and backup relays, respectively. In addition, *F*, *I*, and *S* represent the sets of fault points, all relays, and backup relays, respectively.

DOCRs are deployed in only one direction for different fault points. Consequently, the time-current characteristic of each DOCR is as follows:

$$t^{o,f} = TDS^o \left(\frac{A^o}{(IF^{o,f}/Ip^o)^{B^o} - 1} + C \right) \tag{3}$$

$$O \subset I \tag{4}$$

where o serves as the index for overcurrent relays, and O represents the set of overcurrent relays. $IF^{0,f}$ denotes the fault current sensed by relay o for a fault occurring at point f.

$$\Delta t^{OC/OC, k, F1} = t_b^{o,k,F1} - t_p^{o,k,F1} - CTI_1 \geq 0 \tag{5}$$

$$\Delta t^{OC/OC, k, F4} = t_b^{o,k,F4} - t_p^{o,k,F4} - CTI_1 \geq 0 \tag{6}$$

These statements are the main running constraints in coordination of DOCRs. Satisfying these constraints guarantees the coordination among over-current relays. In these constraints Δt_k is discrimination time among k-th pair relay. Denote that, primary and backup relays are over-current. The other important constraint in coordination of DOCRs and distance relays is as follows:

$$t_p^{o,k,F1} - t_p^{d,k,F1} > 0 \tag{7}$$

$$D \subset I \tag{8}$$

The constraint in (7) is designed to ensure the priority of distance relays over DOCRs within the same station. The constraints outlined in (7) must be fulfilled in F_5. d serves as the index for distance relays, and D represents the set of distance relays. Moreover, the union and closure of these sets should satisfy the following conditions.

$$O \bigcup D = I \tag{9}$$

$$O \bigcap D = 0 \tag{10}$$

Referring to Fig. 3, during faults at F_2 and F_3 the following constraint must be satisfied:

$$\Delta t^{Dis/OC, k, F2} = t_b^{d,k,F2} - t_p^{o,k,F2} - CTI_2 \geq 0 \tag{11}$$

$$\Delta t^{OC/Dis, k} = t_b^{o,k,F3} - t_p^{d,k,F3} - CTI_3 \geq 0 \tag{12}$$

Dis / OC denotes that, primary relay is distance and the backup relay is overcurrent. As well, *OC / Dis* is vice versa. The other technical constraints regarding relays coordination process are as follows:

$$TDS^{min} \leq TDS^o \leq TDS^{max} \tag{13}$$

$$Ip^{min} \leq Ip^o \leq Ip^{max} \tag{14}$$

$$Ip^{min,o} = max(I_{load_o}^{max,o}, Iset^{min}) \tag{15}$$

$$Ip^{max,o} = min(I_F^{min,o}, Iset^{max}) \tag{16}$$

$$T_{Z2}^{min} \leq T_{Z2}^d \leq T_{Z2}^{max} \tag{17}$$

Iset^{min} and *Iset*^{max} are the minimum range and maximum range of pickup current provided by manufacturer on relays. The minimum and maximum of I_p is dependent on system's load current and system's short-circuit capacity. Constraints (3)-(16) are the main basis for extracting the required settings of standard coordination process. In non-standard coordination process which yields non-standard time-current characteristics, parameters A and B are also included in optimization process. To do so, these coefficients are defined as the optimization variables and associated constraints are elaborated by (18), (19):

$$B^{min} \leq B^o \leq B^{max} \tag{18}$$

$$A^{min} \leq A^o \leq A^{max} \tag{19}$$

Eventually, to ensure the security and speed of the proposed protection scheme, the tripping time of each DOCR should also be capped. To do so, the constraint in the following, considers both the lowest and highest permitted times.

$$t^{o,min} \leq t_p^{o,F1} \leq t^{o,max} \tag{20}$$

It is evidently recognized that the proposed coordination scheme for the combinatorial protection scheme represents a non-linear programming problem. In this study, it is solved using the PSO algorithm where details are available in [30]. The particle swarm, established based on the proposed coordination process, is depicted in Fig. 6. It consists five variables, TDS^0, IP^0, A^0, B^0 and T_{z2}^d for both of over-current and distance relay.
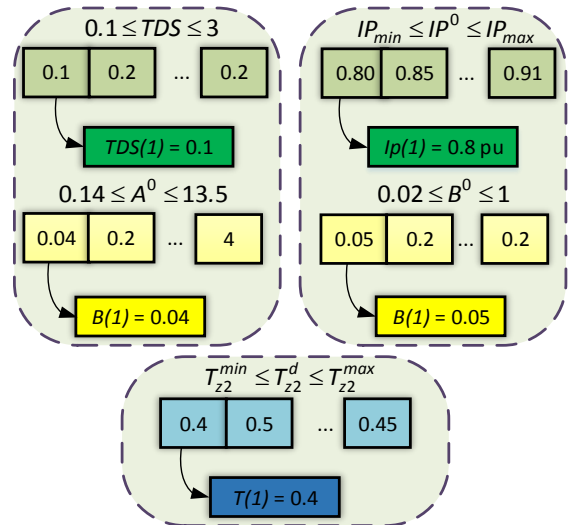

Fig. 6: The proposed particle.

Simulations Results and Discussion

To assess the efficiency and accuracy of the proposed method, it is applied to 8-bus and 9-bus testbeds in two different scenarios. The obtained results based on the proposed method are compared with method presented in [7] in the first scenarios and with [28] in the second scenario. The magnitude of maximum load currents and fault currents have been obtained through DigSILENT Power Factory 14 software. The test networks have been simulated in the mentioned software based on the presented data in [7] and [28]. In short circuit calculation bolted three phase faults are considered in critical points. The optimization process is performed in MATLAB software. It is important to note that, in interconnected power systems, due to significant in-feed (or out-feed) from the connected feeder, distance relays often face mal-operation, which threatens the selectivity of protection systems. For instance, in distance relaying, the location of the critical point F_2 depends on the in-feed (or out-feed) current from the connected feeders to the terminal, that needs to be considered when calculating of Z_2 settings and identifying the critical point F_2. In the current study, the presented method in [18] for setting the second zone of distance relays is employed and hence the effect of in-feed and out-feed on the second zone is considered.

A. First Scenario

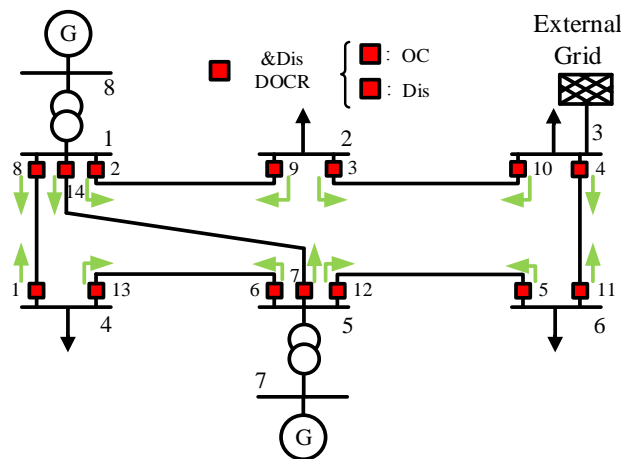The model which is presented in [7] are evaluated based on 8-bus system which is shown in Fig. 7.

Fig. 7: Single line diagram for 8-bus test system.

The depicted arrows in this figure indicate the direction seen by the relays. *TDS*, I_p and T_{Z2} are the variables within the optimization problem. In this scenario, in order to evaluate performance of the proposed model, the best case of presented method in [7] is modeled and solved optimally. This result is then compared with the proposed model. Therefore, the tripping time of the second zone of distance relays is assumed to be between 0.2 and 0.9. For DOCRs, the value of *TDS* can be selected continuously

from 0.1 to 1.1. The maximum and minimum of I_p are calculated in the same manner as presented in [31]. Herein, all the *CTIs* are assumed to be 0.2 sec. Similar to paper [7], the coordination problem is solved for critical points F_1, F_2, and F_3. Table. 2, presents the optimized settings for *TDS*, I_p and T_{Z2} for these critical points. Table. 3 presents the tripping times for faults at those three critical points. The total tripping time of primary overcurrent relays, backup overcurrent relays and second zone of distance relays are 6.4652 sec, 10.2630 sec and 9.5110 sec respectively. As well, in this table, discrimination times for all pairs of relays in all critical points are presented. It is seen that some of the primary/backup pair relays do not satisfy the respective selectivity constraints by maintaining a minimum *CTI* of 0.2 sec. The number of violations is 12, which will not yield reliable protection. The proposed coordination process, as explained in Section 3, is applied to the same test system. In this coordination process, each overcurrent relay set features four settings: TDS, I_p, A, and B, instead of the conventional two settings of *TDS* and I_p. For better comparison, the proposed model is solved in the same critical points considered in [7]. Here, A and B are variables; they have a minimum value of 0.14 and 0.02, and a maximum value of 1 and 13.5, respectively. Table. 4 shows Optimal results for relays in 8-bus test system based on the proposed model. Table. 5 presents the optimal setting of DOCRs and distance relays. As can be seen, the number of violations decreases with the proposed model to 1, demonstrating a significant improvement.

Table 2: Optimal results for relays in 8-bus test system based on presented model in [7]

Relay No.	Parameters		
	TDS	$I_p(A)$	$T_{Z2}(s)$
1	0.1000	446.69	0.7830
2	0.1690	701.74	0.6800
3	0.1020	831.38	0.5660
4	0.1000	931.56	0.8010
5	0.2130	154.51	0.8710
6	0.1000	923.50	0.6660
7	0.3050	116.22	0.6580
8	0.1140	764.50	0.6290
9	0.1890	166.58	0.6630
10	0.1000	780.07	0.6020
11	0.1000	809.78	0.5390
12	0.1470	847.77	0.6200
13	0.1000	483.04	0.8190
14	0.2590	147.89	0.6140

Table 3: Optimal tripping times of primary and backup relays in 8-bus test system based on presented model in [7]

Relay No./ Pair relays		Tripping times for fault @ F_1			Tripping times for fault @ F_2			Tripping times for fault @ F_3		
Primary	Backup	$t_p^{o/c}$	$t_b^{o/c}$	Δt	$t_p^{o/c}$	t_b^{Dis}	Δt	t_p^{Dis}	$t_b^{o/c}$	Δt
1	6	0.3452	0.5480	0.0028	0.3850	0.666	0.0810	0.783	1.2552	0.2722
2	1	0.5348	0.8605	0.1258	0.5585	0.783	0.0245	0.680	2.6733	1.7933
2	7	0.5348	0.7430	0.0082	0.5585	0.658	-0.1005	0.680	0.9283	0.0483
3	2	0.5408	0.7916	0.0507	0.4812	0.680	-0.0012	0.566	0.7826	0.0166
4	3	0.4879	0.6875	-0.0004	0.5030	0.566	-0.1370	0.801	1.1182	0.1172
5	4	0.528	0.7295	0.0015	0.5439	0.801	0.0571	0.871	1.2098	0.1388
6	5	0.3602	0.7594	0.1992	0.3831	0.871	0.2879	0.666	2.3276	1.4616
6	14	0.3602	0.7107	0.1505	0.3831	0.614	0.0309	0.666	1.0458	0.1798
7	5	0.5398	0.7406	0.0008	0.5650	0.871	0.1060	0.658	0.7719	-0.0861
7	13	0.5398	1.2747	0.5349	0.5650	0.819	0.0540	0.658	-	-
8	7	0.3753	0.7444	0.1691	0.3993	0.658	0.0587	0.629	1.1381	0.3091
8	9	0.3753	0.6792	0.1039	0.3993	0.663	0.0637	0.629	-	-
9	10	0.5129	0.7139	0.0009	0.4907	0.602	-0.0887	0.663	0.9343	0.0713
10	11	0.4246	0.6279	0.0033	0.4354	0.539	-0.0964	0.602	0.9422	0.1402
11	12	0.4388	0.6648	0.026	0.4511	0.620	-0.0311	0.539	0.7541	0.0151
12	13	0.5095	0.9712	0.2618	0.5325	0.819	0.0865	0.620	2.9109	2.0909
12	14	0.5095	0.7107	0.0013	0.5325	0.614	-0.1185	0.620	0.8604	0.0404
13	8	0.3752	0.5734	-0.0018	0.4026	0.629	0.0264	0.819	1.1190	0.1000
14	1	0.4921	1.0673	0.3752	0.5168	0.783	0.0662	0.614	-	-
14	9	0.4921	0.6922	0.0001	0.5168	0.663	-0.0538	0.614	0.7250	-0.0890

Table 4: Optimal results for relays in 8-bus test system based on the proposed model

Relay No.	Parameters				
	TDS	$I_p(A)$	A	B	T_{Z2} (s)
1	0.3311	399.3074	1.5748	0.8090	0.9000
2	0.4166	758.9497	3.2718	0.8591	0.6537
3	0.2618	787.1245	2.6239	0.7495	0.6225
4	0.2544	830.192	3.0266	0.7617	0.6919
5	0.3617	153.1538	5.4828	0.7062	0.8999
6	0.3762	914.6058	2.5562	1.0000	0.8997
7	0.5774	69.4785	5.3969	0.5561	0.4991
8	0.2275	736.9103	3.9123	0.8411	0.3728
9	0.4083	216.5528	3.3756	0.6516	0.7781
10	0.2980	795.0116	2.5574	0.7947	0.6620
11	0.3240	817.8852	2.4128	0.8630	0.5268
12	0.4276	722.4855	4.0185	0.8052	0.6887
13	0.3830	421.7058	1.3544	0.7566	0.8216
14	0.4895	165.9199	6.1853	0.7606	0.6059

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The mentioned violations in Table. 3 and Table. 5 are highlighted in gray. Additionally, the total tripping time of primary overcurrent relays, backup overcurrent relays, and the second zone of distance relays in the proposed model are 2.8045 sec, 6.1459 sec, and 7.4454 sec, respectively, showing a significant reduction of approximately 56.6%, 40%, and 21.7%. This demonstrates the efficiency of the proposed scheme. These remarks confirm the satisfactory performance of the proposed approach in reducing violations and shortening relay tripping times, thereby ensuring a reliable and fast protection scheme. Fig. 8, depict comparisons of relay tripping times between the proposed approach and the conventional method at three critical points. Fig. 8d-f, demonstrate comparisons of discrimination times between the proposed approach and the conventional method. As seen in Fig. 8e, the discrimination times in the conventional approach are shorter than those in the proposed approach. However, most of the discrimination times in the conventional approach have negative values.

Table 5: Optimal tripping times of primary and backup relays in 8-bus test system based on the proposed model

Relay No./ Pair relays		Result for fault @ F_1			Result for fault @ F_2			Result for fault @ F_3		
Primary	Backup	$t_p^{o/c}$	$t_b^{o/c}$	Δt	$t_p^{o/c}$	t_b^{Dis}	Δt	t_p^{Dis}	$t_b^{o/c}$	Δt
1	6	0.1167	0.3750	0.0582	0.1431	0.8997	0.5566	0.9000	1.2684	0.1684
2	1	0.2724	0.4727	0.0003	0.2991	0.9000	0.4009	0.6537	1.4792	0.6255
2	7	0.2724	0.5884	0.1160	0.2991	0.4991	0.0000	0.6537	0.8541	0.0005
3	2	0.3889	0.5892	0.0004	0.3245	0.6537	0.1292	0.6225	0.5774	-0.245
4	3	0.3489	0.5491	0.0002	0.3656	0.6225	0.0569	0.6919	1.0160	0.1241
5	4	0.3304	0.6150	0.0847	0.3526	0.6919	0.1393	0.8999	1.1125	0.0126
6	5	0.1659	0.6790	0.3131	0.1894	0.8999	0.5105	0.8997	3.4349	2.3352
6	14	0.1659	0.5961	0.2302	0.1894	0.6059	0.2164	0.8997	1.2886	0.1890
7	5	0.3099	0.6490	0.1391	0.3427	0.8999	0.3573	0.4991	0.6991	0.0000
7	13	0.3099	0.7683	0.2583	0.3427	0.8216	0.2789	0.4991	-	-
8	7	0.1800	0.5904	0.2105	0.2041	0.4991	0.0950	0.3728	1.1511	0.5783
8	9	0.1800	0.7149	0.3349	0.2041	0.7781	0.3740	0.3728	-	-
9	10	0.4127	0.6738	0.0612	0.3760	0.6620	0.0860	0.7781	0.9787	0.0006
10	11	0.2961	0.4988	0.0028	0.3093	0.5268	0.0175	0.6620	0.8950	0.0330
11	12	0.2750	0.5963	0.1213	0.2888	0.6887	0.1999	0.5268	0.7271	0.0004
12	13	0.3734	0.5736	0.0002	0.4057	0.8216	0.2159	0.6887	1.5779	0.6892
12	14	0.3734	0.5961	0.0227	0.4057	0.6059	0.0002	0.6887	0.8895	0.0008
13	8	0.1512	0.3916	0.0404	0.1707	0.3728	0.0021	0.8216	1.0217	0.0000
14	1	0.2387	0.6100	0.1713	0.2732	0.9000	0.4268	0.6059	-	-
14	9	0.2387	0.7405	0.3018	0.2732	0.7781	0.3049	0.6059	0.8060	0.0002

Table 6: Optimal results for relays in 9-bus test system based on the presented model in [28]

Relay No.	Parameters		
	TDS	$I_P(A)$	No. of characteristic
1	0.530	226.149	8
2	0.130	236.750	6
3	0.249	105.625	6
4	1.180	71.160	4
5	0.358	186.703	8
6	0.150	181.320	6
7	0.610	108.486	1
8	1.060	93.2480	4
9	0.270	140.056	3
10	0.350	169.800	1
11	0.300	257.400	1
12	0.184	255.480	8

Table 7: Optimal results for relays in 9-bus test system based on the proposed model

Relay No.	Parameters				
	TDS	$I_P(A)$	A	B	T_{Z2}
1	2.240	242.970	0.971	1.000	0.508
2	0.061	227.280	0.140	0.020	0.490
3	0.963	101.400	0.512	0.405	0.499
4	1.724	77.090	3.866	1.000	0.505
5	1.287	200.590	1.203	1.000	0.531
6	0.826	181.320	1.014	0.812	0.594
7	1.458	103.320	0.731	0.746	0.486
8	2.483	97.760	2.038	1.000	0.522
9	1.206	149.240	2.491	1.000	0.484
10	0.776	169.800	0.741	0.651	0.508
11	0.587	257.400	0.919	0.843	0.553
12	2.253	276.770	0.507	1.000	0.538

Table 8: Comparison of discrimination times of relays

Pair relays		Δt @									
PR	BR	F_1		F_2		F_3		F_4		F_5	
		[28]	New	[28]	New	[28]	New	[28]	New	[28]	New
1	11	0	0	0.666	1.593	0.126	0.256	0.331	0.679	-0.3635	0
2	4	0.055	0.047	0.318	0.195	0.076	0.319	0	0	-0.3636	0
3	1	0	0	0.676	0.306	0.190	0.261	0.440	0.066	-0.3427	0
4	6	0	0	0.400	1.242	0.071	0.279	0.129	0.616	-0.3694	0
5	3	0.003	0	0.068	0.469	0.041	0.160	0.011	0.109	-0.3547	0
6	8	0	0	0.358	0.251	0.159	0.213	0.226	0	-0.3040	0
7	5	0	0	0.377	0.200	0.188	0.279	0.251	0.024	-0.4151	0
8	10	0	0	0.472	0.920	0.173	0.209	0.297	0.372	-0.3160	0
9	7	0	0	0.397	0.493	0.099	0.199	0.273	0.176	-0.3258	0
10	12	0	0	0.278	0.228	0.295	0.284	0.274	0.032	-0.3210	0
11	9	0	0	1.156	0.241	0.172	0.180	0.777	0	-0.2851	0
12	2	-0.31	0	-	-	-0.17	0.146	0.590	4.162	-0.3259	0
Average (for positive values)		0.01	0.004	0.437	0.511	0.346	0.232	0.490	0.520	-	0

(a) Tripping time at F_1

(b) Tripping time at F_2

(c) Tripping time at F_3

(d) Discrimination times for F_1

(e) Discrimination times for F_2
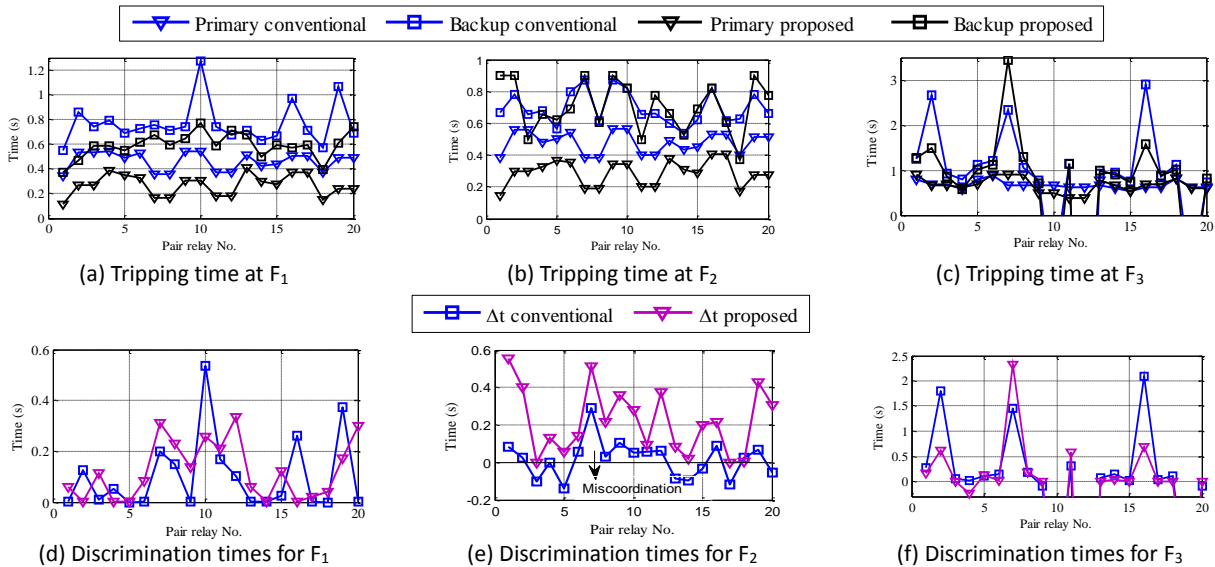
(f) Discrimination times for F_3

Fig. 8: Comparison of the proposed approach versus the conventional method in three critical point.

B. Second Scenario

Here, the proposed method is compared with those presented in [28]. In [28], characteristics of relays can be chosen from Table. 1.

Furthermore, the optimization process takes into account all five critical points. The 9-bus test system is considered as testbed which is depicted in Fig. 9, where detailed in [28]. Like Fig. 7, The arrows in this figure indicate the direction seen by the relays.
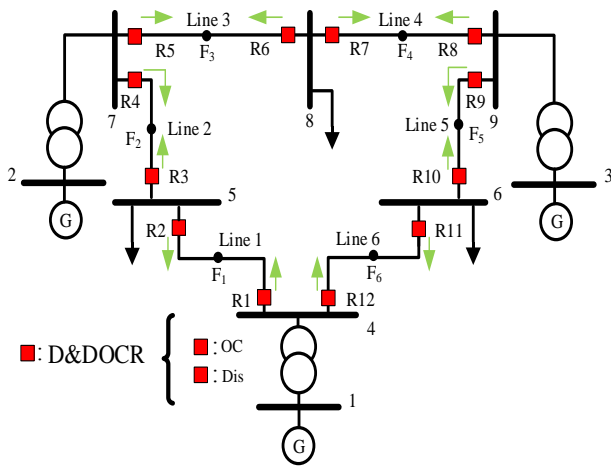

Fig. 9: Single line diagram for 9-bus test system.

TDS and I_p can range from 0.1 to 3.2 and $1.2 \times I_p$ to $1.3 \times I_p$ respectively. The value of T_{Z2} is set at 0.3 sec.

Optimized variable values are listed in Table. 6 and Table. 7, where Table. 6 is corresponding for conventional scheme and Table. 7 shows optimal results for relays in the 9-bus test system based on the proposed model. All the *CTIs* are assumed 0.2 sec.

Discrimination time of pair relays in five critical fault points is given in Table. 8.

As observed, 14 pairs of relays are not satisfied selectivity constraint. The proposed model is applied to the 9-bus testbed using the same objective function in [28].

Thus, besides *TDS* and I_p, the other variables *A*, *B*, and T_{Z2}, are also included in the optimization problem. The obtained solution is also given in Table. 7. As it is seen All coordination constraints are satisfied and there is no miscoordinations which yields reliable protection. The overall average discrimination time of relays, which were previously positive according to the model presented in [28], has been reduced from 1.283 sec to 1.267 sec. This study primarily focuses on the technical aspects of the combinatorial protection scheme in sub-transmission systems and does not extensively address the cost implications or economic feasibility of implementing the proposed solutions with employment of numerical relays. Future research should include a comprehensive economic analysis to evaluate the financial viability of these protection measures.

Conclusion

This study concerns relaying problem in protection scheme of over-current and distance relays in the sub-transmission system. In this paper, based on the provided flexibility by numerical relays, DOCRs was encouraged to follow user defined characteristics. Specifically, the constant coefficients of the DOCRs characteristic are considered as optimization variables, leading to a non-standard coordination process with greater flexibility. In this process relays are coordinated in five critical points to assure selectivity along the protected lines. The proposed approach is compared with conventional approaches in two different case studies. In both case studies, the discrimination time and the total tripping time of the relays have been reduced. Furthermore, in the first case study, the number of violations decreased from 12 to 1. Also, in the second case study, the number of violations has been reduced from 14 to zero. The obtained results highlight that:

- Number of pair relays satisfying selectivity constraints were increased and number of violations were decreased resulting in reliable protection scheme;
- A significant reduction in the total tripping time of relays, contributing to a faster protection system;
- Discrimination time of relays were also diminished.

Author Contributions

A. Yazdaninejadi has contributions on modeling, simulations, performing the analysis and writing the paper. M. Akhavan has contributions on modeling, simulations, performing the analysis and writing the paper.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

DOCR	Directional Overcurrent Relay
PSO	Particle Swarm Optimization
IED	Intelligent Electronic Device
CTI	Critical Time Interval

T_{Z2}	Time Setting for The Second Zone of Distance Relay
Z_{2b}	Second Zone of The Backup Distance Relay
Z_{2p}	Second Zone of the Primary Distance Relay
TDS	Time Dial Setting
SI	Standard-Inverse
VI	Very-Inverse
EI	Extremely-Inverse

References

[1] H. Sahraei, M. Tolou Askari, "Influence of phase-shifting transformers on the distance protection of transmission lines and improve the performance of distance relay, " J. Electr. Comput. Eng. Innovations, 9(2): 173-184, 2021.

[2] T. S. Sidhu, R. K. Varma, P. K. Gangadharan, F. A. Albasri, G. R. Ortiz, "Performance of distance relays on shunt-FACTS compensated transmission lines," IEEE Trans. Power Deliv., 20(3): 1837-1845, 2005.

[3] S. M. Brahma, "Distance relay with out-of-step blocking function using wavelet transform," IEEE Trans. Power Deliv., 22(3): 1360-1366, 2007.

[4] D. Kang, R. Gokaraju, "A new method for blocking third-zone distance relays during stable power swings," IEEE Trans. Power Deliv., 31(4): 1836-1843, 2016.

[5] P. P. Bedekar, S. R. Bhide, V. S. Kale, "Optimum coordination of overcurrent relay timing using simplex method," Electr. Power Compon. Syst., 38(10): 1175-1193, 2010.

[6] P. P. Bedekar, S. R. Bhide, V. S. Kale, "Optimum coordination of overcurrent relays in distribution system using dual simplex method, " in Proc. 2009 Second International Conference on Emerging Trends in Engineering & Technology: 555-559, 2009.

[7] M. Farzinfar, M. Jazaeri, F. Razavi, "A new approach for optimal coordination of distance and directional over-current relays using multiple embedded crossover PSO," Int. J. Electr. Power Energy Syst., 61: 620-628, 2014.

[8] S. A. Ahmadi, H. Karami, M. J. Sanjari, H. Tarimoradi, G. B. Gharehpetian, "Application of hyper-spherical search algorithm for optimal coordination of overcurrent relays considering different relay characteristics," Int. J Electr. Power Energy Syst., 83: 443-449, 2016.

[9] F. A. Albasri, A. R. Alroomi, J. H. Talaq, "Optimal coordination of directional overcurrent relays using biogeography-based optimization algorithms," IEEE Trans. Power Deliv., 30(4): 1810-1820, 2015.

[10] M. Alipour, S. Teimourzadeh, H. Seyedi, "Improved group search optimization algorithm for coordination of directional overcurrent relays," Swarm Evol. Comput., 23: 40-49, 2015.

[11] D. K. Ibrahim, E. E. Din Abo El Zahab, S. Abd El Aziz Mostafa, "New coordination approach to minimize the number of re-adjusted relays when adding DGs in interconnected power systems," J. Electr. Eng. Technol., 12(2): 502-512, 2017.

[12] A. Papaspiliotopoulos, G. N. Korres, N. G. Maratos, "A novel quadratically constrained quadratic programming method for optimal coordination of directional overcurrent relays," IEEE Trans. Power Deliv., 32(1): 3-10, 2015.

[13] C. W. So, K. K. Li, "Overcurrent relay coordination by evolutionary programming," Electr. Power Syst. Res., 53(2): 83-90, 2000.

[14] M. Y. Shih, C. A. Castillo Salazar, A. C. Enríquez, "Adaptive directional overcurrent relay coordination using ant colony optimisation," IET Gener. Transm. Distrib., 9(14): 2040-2049, 2015.

[15] D. S. Alkaran, M. R. Vatani, M. J. Sanjari, G. B. Gharehpetian, M. S. Naderi, "Optimal overcurrent relay coordination in interconnected networks by using fuzzy-based GA method," IEEE Trans. Smart Grid, 9(4): 3091-3101, 2016.

[16] L. G. Perez, A. J. Urdaneta, "Optimal coordination of directional overcurrent relays considering definite time backup relaying," IEEE Trans. Power Deliv., 14(4): 1276-1284, 1999.

[17] L. G. Perez, A. J. Urdaneta, "Optimal computation of distance relays second zone timing in a mixed protection scheme with directional overcurrent relays," IEEE Trans. Power Deliv., 16(3): 385-388, 2001.

[18] Z. Moravej, M. Jazaeri, M. Gholamzadeh, "Optimal coordination of distance and over-current relays in series compensated systems based on MAPSO," Energy Conv. Manag., 56: 140-151, 2012.

[19] H. A. Darwish, M. Fikri, "Practical considerations for recursive DFT implementation in numerical relays," in Proc. 2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition: 880-887, 2006.

[20] S. Dadfar, M. Gandomkar, "Augmenting protection coordination index in interconnected distribution electrical grids: Optimal dual characteristic using numerical relays," Int. J. Electr. Power Energy Syst., 131:107107, 2021.

[21] M. A. Abdel-Salam, R. Kamel, K. Sayed, M. Khalaf, "Design and implementation of a multifunction DSP-based-numerical relay," Electr. Power Syst. Res., 143: 32-43, 2017.

[22] Y. L. Goh, A. K. Ramasamy, F. H. Nagi, A. A. Zainul Abidin, "Evaluation of DSP based numerical relay for overcurrent protection," Int. J. Syst. Appl. Eng. Dev., 5: 396-403, 2011.

[23] SIPROTEC Multi-Functional Protective Relay 7SJ62/63/64 [Online].

[24] Toshiba directional overcurrent relay GRD 140 [Online].

[25] M. Ojaghi, R. Ghahremani, "Piece-wise linear characteristic for coordinating numerical overcurrent relays," IEEE Trans. Power Deliv., 32(1): 145-151, 2016.

[26] C. A. Castillo Salazar, A. Conde Enríquez, S. E. Schaeffer, "Directional overcurrent relay coordination considering non-standardized time curves," Electric. Power Syst. Res., 122: 42-49, 2015.

[27] A. Yazdaninejadi, D. Nazarpour, S. Golshannavaz, "Dual-setting directional over-current relays: An optimal coordination in multiple source meshed distribution networks," Int. J. Electr. Power Energy Syst., 86: 163-176, 2017.

[28] S. A. Ahmadi, H. Karami, B. Gharehpetian, "Comprehensive coordination of combined directional overcurrent and distance relays considering miscoordination reduction," Int. J. Electr. Power Energy Syst., 92: 42-52, 2017.

[29] Y. Damchi, J. Sadeh, H. Rajabi Mashhadi, "Optimal coordination of distance and overcurrent relays considering a non-standard tripping characteristic for distance relays," IET Gener. Transm. Distrib., 10(6): 1448-1457, 2016.

[30] M. Hasanluo, F. Soleimanian Gharehchopogh, "Software cost estimation by a new hybrid model of particle swarm optimization and k-nearest neighbor algorithms," J. Electr. Comput. Eng. Innovations, 4(1): 49-55, 2016.

[31] P. P. Bedekar, S. R. Bhide, "Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach," IEEE Trans. Power Deliv., 26(1): 109-119, 2010.

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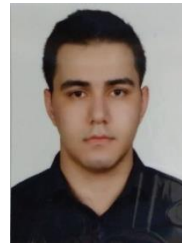
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