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Comprehensive coordination of combined directional overcurrent and distance relays considering miscoordination reduction

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ABSTRACT

This paper presents a novel approach to solve the miscoordination problem of combined directional overcurrent and distance relays in transmission and subtransmission systems. In order to reduce relays miscoordinations, a general objective function is presented to find optimum directional overcurrent relays time setting multipliers, characteristics, and pickup currents by optimization algorithms. In previous researches, different approaches have been presented but they cannot find a reliable solution to avoid from having negative discrimination times between the backup and main relay (miscoordination), which means operation of the backup relay before the main relay. Using proposed approach, not only the number of miscoordinations can be greatly decreased but also the positive discrimination times can be minimized. The proposed method is tested on 9-bus and 39-bus test system. Genetic algorithm and human behavior-based optimization are used as optimization tools to find optimum settings. The results indicate that the proposed approach is capable of solving the miscoordination problem, in addition to minimization of discrimination and relay operation times compared with previous approaches.

1. Introduction

Well coordination of relays is the procedure of finding the suitable settings, which result in the operation of the nearest relay to the fault location before other primary relays. Directional overcurrent and distance relays play an important role in protection of transmission and subtransmission power systems; therefore, their coordination should be seriously taken into consideration. To achieve a safe protection of power systems, a common solution is the application of a backup protection beside the main protection [1,2]. In transmission and subtransmission lines, directional overcurrent and distance relays are mainly used for protection. In this protection scheme, the directional overcurrent relays and the first zone of the distance relays are used for the main protection. In addition, the directional overcurrent relays with a delay time, and the second zone of the distance relays are used as backup protection.

In order to have a reliable protection, the backup relay should not operate before the main relay. For this, a coordination time interval (*CTI*) [3–5] should be added to the operation time. For overcurrent relays optimal coordination, valuable researches have been conducted based on the linear programming techniques like simplex [6] and dual simplex [7] methods.

To achieve comprehensive coordination, both directional overcurrent and distance relays should be coordinated, and the discrimination time between the backup and main relay should not be less than *CTI* [8,9]. In coordination problems, the aim is to minimize the discrimination time (Δt) between the backup and main relay. So the coordination problem can be considered as an optimization problem, which can be solved by artificial intelligence methods. In these methods the coordination constrains are involved in the objective function (OF) [10].

In [11], an approach has been introduced for only the coordination of the overcurrent relays and the time setting multipliers (*TSMs*) have been selected by using evolutionary algorithms. In [12], another approaches have been introduced and the same approach has been used by using genetic algorithm (GA). In [13], the overcurrent relays coordination has been achieved by particle swarm optimization (PSO) method, as meta-heuristic algorithm, and the *TSMs* have been selected. In [1], hyper-spherical search algorithm has been used to coordinate overcurrent relays considering different relay characteristics. In [5], critical fault point for calculation of short circuit current has been investigated using an analytical approach and overcurrent relays have been coordinated considering the calculated critical fault current.

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In all aforementioned papers, the optimal coordination has been performed only for overcurrent relays, while in power transmission and subtransmission lines, the overcurrent and distance relays are simultaneously used in protection schemes. Therefore, both of them should be coordinated. In addition, the characteristic of the relays and the pickup currents have been assumed to be fix, and only the *TSMs* have been optimally selected.

In [14], the optimal coordination of the overcurrent relays and the second zone of the distance relays have been studied using linear programming techniques, and the *TSMs* have been selected. In [15], by using a new OF, the coordination of both the overcurrent and distance relays have been optimized using GA, and the *TSMs* and the characteristics of the overcurrent relays have been selected, but still the pickup currents have been assumed to be fixed values.

In all mentioned papers, the miscoordinations are still the main problem and has not been solved. Some the relays in the previous works meet the miscoordination problem. In this paper, a new approach for coordination of combined directional overcurrent and distance relays will be introduced and GA and human behavior-based optimization (HBBO), as the optimization algorithms, will be used to find the best *TSMs* as well as best characteristics of the directional overcurrent relays and pickup currents. It will be shown that by using the proposed approach, the miscoordination will be decreased, and the discrimination times will be minimized and in many cases, it will be close to zero. In addition, it will be shown that by selecting the proper pickup currents, the coordination will be improved. It should be noted that this paper investigates the steady-state condition of the system for relay coordination. Similar to the previous works [16], at first the proper approach for optimal coordination of the power system should be found and then in another study, the proper approach to adapt the proposed approach should be discussed. Transient behavior will be our future work.

The contributions of the paper can be summarized as follows:

- Considering miscoordination reduction in the coordination of distance and directional overcurrent relays problem
- Optimally selecting pickup currents for each directional overcurrent relay in the proposed approach.
- Simultaneously considering optimal selection of overcurrent pickup current, characteristics, *TSMs* and miscoordination reduction in the proposed approach.
- Applying a novel optimization algorithm to the problem of relay coordination and comparing its results with GA.

2. Problem statement

In power networks, both the directional overcurrent and distance relays can operate as the main or backup relays; therefore, it will be four different types of protection scheme.

Type 1: Main directional overcurrent relay and backup directional overcurrent relay (OC-OC protection type)
Type 2: Main directional overcurrent relay and backup distance relay (Dis-OC protection type)
Type 3: Main distance relay and backup directional overcurrent relay (OC-Dis protection type)
Type 4: Main distance relay and backup distance relay (Dis-Dis protection type)

The coordination of the Dis-Dis protection type should be performed before the coordination of others and the impedance settings for three zones of the distance relays should be calculated. These settings will be used for the coordination of the remaining protection types. To calculate the directional overcurrent relay operation time, the fault locations should be specified. These fault locations, specified in [15,13], are shown in Figs. 1 and 2. Then, the discrimination times between the backup and main relays, for each fault locations should be checked for OC-OC protection type as follows:

$$t_{bOC|F_1|} - t_{mOC|F_1|} \geqslant CTI_1 \tag{1}$$

$$t_{bOC|F_2|} - t_{mOC|F_2|} \geqslant CTI_1 \tag{2}$$

where $t_{bOC|F_i|}$ and $t_{mOC|F_i|}$ are the backup and main directional overcurrent relays operation times for the fault that occurs in the location F_i, and the CTI_1 is the coordination time interval of the OC-OC protection type. For OC-Dis protection type, the following expressions should be checked:

$$t_{bOC|F_3|} - t_{z_1} \geqslant CTI_2 \tag{3}$$

$$t_{bOC|F_4|} - t_{z_2} \geqslant CTI_2 \tag{4}$$

where t_{z_1} and t_{z_2} are the distance relays operation times for the first and second zones, and the CTI_2 is the coordination time interval of the OC-Dis protection type. At last, for the Dis-OC protection type, the following expression should be checked:

$$t_{z_2} - t_{mOC|F_5|} \geqslant CTI_3 \tag{5}$$

where CTI_3 is the coordination time interval of the Dis-OC protection type.

3. Proposed method

As it mentioned before, the negative discrimination time means that the backup relay operates before the main relay. Therefore, in coordination process, it is necessary to minimize the number of these miscoordinations, and then, the discrimination times, and also the operation times of the relays should be minimized.

In proposed OF, for each protection type, the number of negative discrimination times will be counted. Then its value will be increased by an amplification factor, namely γ, and it will be a penalty factor for both discrimination times and the operation times. This OF is formulated as follows:

For OC-OC protection type:

$$OF_{oc-oc} = (m_1 + 1)^{\gamma_1} \times \left(\alpha \sum_{i=1}^{N} t_i + \beta_1 \sum_{k_1=1}^{P_1} \left| \Delta t_{mbOC|F_1|} \right| + \beta_2 \sum_{k_1=1}^{P_1} \left| \Delta t_{mbOC|F_2|} \right| \right) \tag{6}$$

It will guaranty the constraints (1) and (2). For OC-Dis protection type, we have:

$$OF_{oc-dis} = (m_2 + 1)^{\gamma_2} \times \left(\beta_3 \sum_{k_2=1}^{P_2} \left| \Delta t_{mbOCDis|F_3|} \right| + \beta_4 \sum_{k_2=1}^{P_2} \left| \Delta t_{mbOCDis|F_4|} \right| \right) \tag{7}$$

It will guaranty the constraints (3) and (4). For Dis-OC protection type, the OF is the same as one proposed in [15] that will guaranty the constraint (5):

$$OF_{dis-oc} = \beta_5 \sum_{k_3=1}^{P_3} \left| \Delta t_{mbDisOC|F_4|} \right| \tag{8}$$

where $\Delta t_{mbOC|F_i|}$ is the discrimination time of directional overcurrent relays in OC-OC protection type for the fault occurred at the location F_i and can be obtained as follows:

$$\Delta t_{mbOC|Fi|} = t_{bOC|F_i|} - t_{mOC|F_i|} - CTI_1 \tag{9}$$

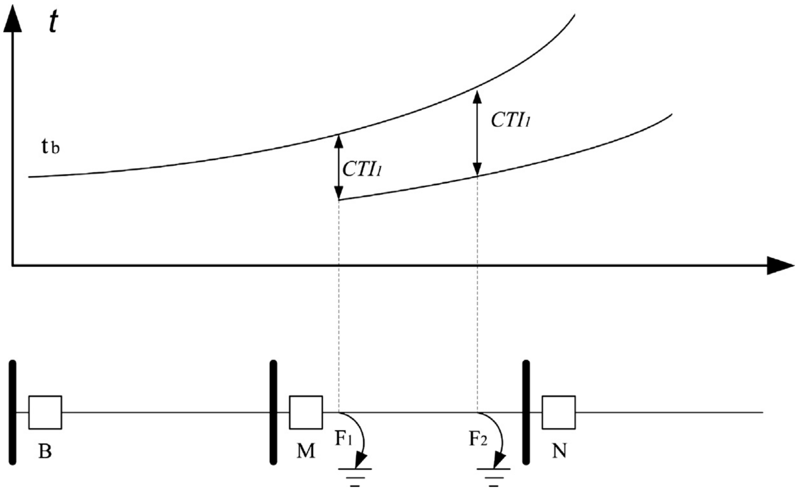


Fig. 1. Fault locations for coordination of OC-OC protection type.

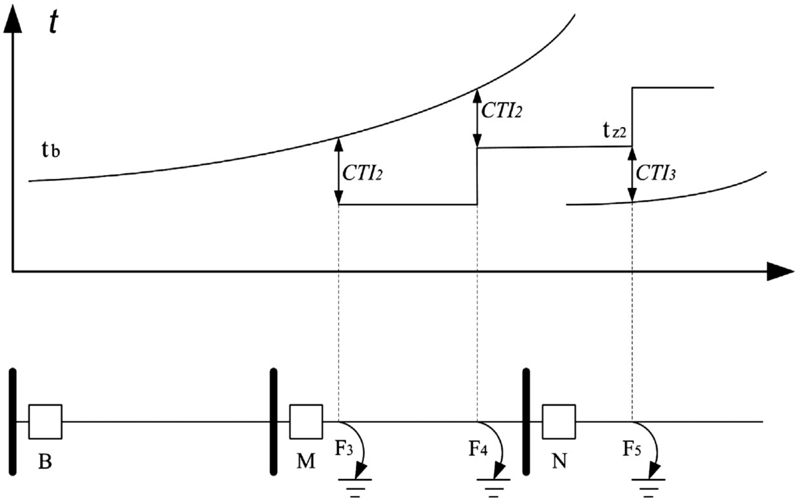


Fig. 2. Fault locations for coordination of OC-Dis and Dis-OC protection type.

m_1 is the number of negative $\Delta t_{mbOC|F_i|}$ and γ_1 is the amplification factor for the number of these miscoordinations occurred in this protection type. $\Delta t_{mbOCDis|F_i|}$ is the discrimination time between the backup directional overcurrent relay and main distance relay in OC-Dis protection type for the fault occurred at the location F_i and can be obtained by the following equation:

$$\Delta t_{mbOCDis|Fi|} = t_{bOC|F_i|} - t_{mDis|F_i|} - CTI_2 \tag{10}$$

m_2 is the number of the negative $\Delta t_{mbOCDis}$ and γ_2 is the amplification factor for the number of these miscoordinations occurred in this protection type. $\Delta t_{mbDisOC}$ is used to decrease the operation times of the second zone of the distance relays in Dis-OC protection type, and can be obtained as follows:

$$\Delta t_{mbDisOC} = t_{z_2} - CTI_3 \tag{11}$$

where t_{z_2} is the operation time for the second zone of the distance relay and according to [15], for each generation of GA, it is as follows:

$$t_{Z_2} = max((t_m(F_5) + CTI_3) + t_Z) \tag{12}$$

where t_Z is the initial time of the second zone of the distance relay.

Other parameters are defined as follows:

i:	Number of directional overcurrent relays that changes from 1 to N
k_1:	Number of directional overcurrent relays pair in OC-OC protection type that changes from 1 to P_1
k_2:	Number of backup directional overcurrent and main distance relays pair in OC-Dis protection type that changes from 1 to P_2
k_3:	Number of distance relays pair in Dis-Dis protection type that changes from 1 to P_3
$\alpha, \beta_1, \ldots, \beta_5$:	Weighting factors

As it can be seen in (9) and (10), discrimination times can be positive or negative according to settings of the main and backup relays and the value of the *CTI*. If the discrimination time is negative, it means that the time difference between operation of main and backup relays is lower than predefined value, *CTI*, and this is a miscoordination. Number of miscoordinations is calculated by m1 and m2 in the OF. If the discrimination time between two relays is positive, it means that time difference between operation of main and backup relays is equal or higher than CTI and these two relays are coordinated. It is important to reduce this positive discrimination time to consequently reduce the time operation of main and backup relays where facing a fault current. In this OF, the highest importance is the minimization of the number of miscoordinations and after that, the positive discrimination times and also the operation times will be minimized.

It should be noted that in all previously introduced OF-s, the penalty factors have been considered to be fix. However, in this OF, the value of the penalty factor is increased by increasing the number of the miscoordinations. This consideration leads to decrease the number of miscoordinations significantly. If the fault currents are calculated previously, there is no need to calculate their values. otherwise, the fault current should be calculated before calculating the operation time of relays. A simplified flowchart of this method is shown in Fig. 3.

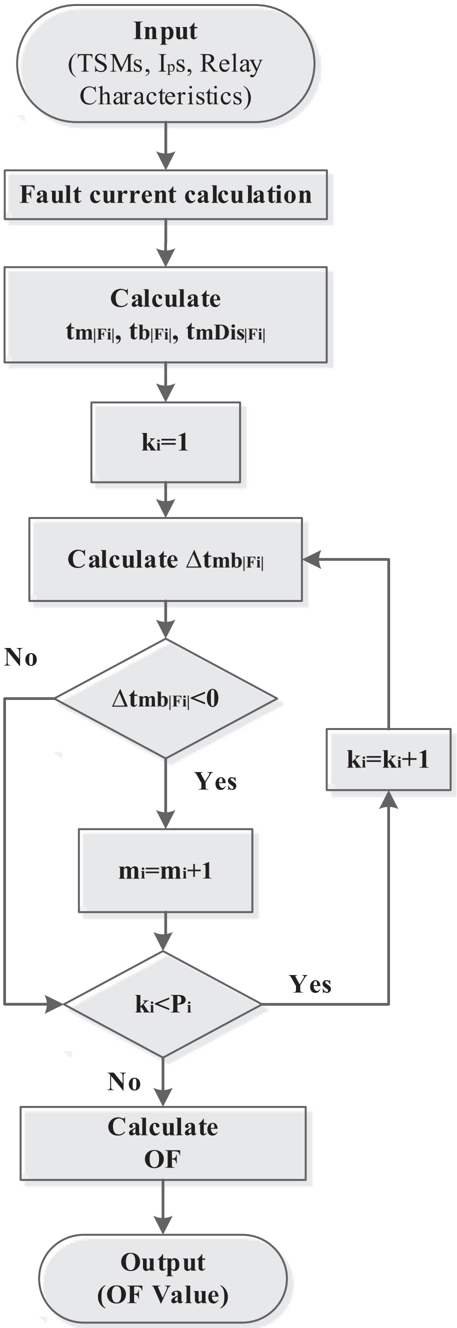


Fig. 3. Flowchart of proposed method.

Now the OF is ready to be optimized by using optimization algorithm. For directional overcurrent relays, the operation time can be calculated by the following equation:

$$t = TSM\left(\frac{K}{M^{\alpha}-1}+L\right) \tag{13}$$

where K, α and L depend on the relay characteristic that are given in Table 1, and M is the ratio of the short circuit current I_{SC} to the pickup current I_{pickup} of the directional overcurrent relay:

$$M = \frac{I_{sc}}{I_{pickup}} \tag{14}$$

I_{pickup} can be obtained by the following equation:

$$I_{pickup} = I_{pf} \times I_n \tag{15}$$

where I_n is the nominal current and I_{pf} is the pickup current factor. In this OF, upper and lower limits of pickup current are as follows:

$$I_{pf_{\min}} \leqslant I_{pf} \leqslant I_{pf_{\max}} \tag{16}$$

where I_{pfmin} and I_{pfmax} in this paper are 1.2 and 1.3, respectively.

Similar to the pickup current, all the *TSMs* should be selected considering following constraints:

$$TSM_{\min} \leqslant TSM \leqslant TSM_{\max} \tag{17}$$

where TSM_{min} and TSM_{max} in this paper are 0.05 and 2, respectively.

It should be noted that in the microprocessor based relays, the pickup current is continuous in nature. In other words, in the electromechanical relays, pickup current can be only chosen from discrete values but the microprocessor based relays provide the ability of choosing continuous values.

4. Applying optimization algorithms to relay coordination problem

4.1. Applying GA to the problem

GA is a popular optimization algorithm which has been used in several engineering problems [17,18]. Optimization algorithm in this paper is a tool for finding suitable settings of the relays. Something which is interesting for optimization tools, is whether the proposed methodology can obtain an optimum answer or not. Genetic algorithm shows its performance in coordination problems and for this it has been widely used by researches such as [10,11,15]. In this section, for a better understanding of results, the application of the GA for relay coordination problem is presented.

The GA starts with randomly generation of individuals, which form the initial population. Every individual is linked to the chromosomes and the variables are the genes of these chromosomes. In the directional overcurrent relays coordination problem, the *TSMs*, the pickup currents and the relay characteristics are the genes of the chromosomes.

After generating the initial population, the algorithm evolves through three operators, as follows:

1. *Selection:* this operator gives preference to the better individuals which have the lower function values and allows them to be in the next generation.
2. *Crossover:* this operator produce the new individuals by recombining the positions of the individuals and is likely to generate better individuals.

Table 1
Characteristics of the overcurrent relays.

Number of characteristic	Type of characteristic	Standard	K factor	α factor	L factor
1	Short Time Inverse	AREVA	0.05	0.04	0
2	Standard Inverse	IEC	0.14	0.02	0
3	Very Inverse	IEC	13.5	1	0
4	Extremely Inverse	IEC	80	2	0
5	Long Time Inverse	AREVA	120	1	0
6	Moderately Inverse	ANSI/IEEE	0.0515	0.02	0.114
7	Very Inverse	ANSI/IEEE	19.61	2	0.491
8	Extremely Inverse	ANSI/IEEE	28.2	2	0.1217

(3) *Mutation:* whit some low probability, random modifications will be occurred whit this operator. Similar to the crossover, this operator may generate better individuals and lead to the better result.

Finally, the variables that have the minimum value of the OF will be selected. This process will be terminated when the number of iterations reaches to the number of generations.

In this paper, the GA will select *TSMs* in the range of 0.05–2 and also will select the relay characteristics by choosing the best M, α and L from Table 1, and the pickup currents will be selected by choosing the best I_{pf}-s in the range of 1.2–1.3. The chromosome structure is shown in Fig. 4.

4.2. Applying HBBO to the problem

HBBO is a newly introduced optimization approach [19], and is used in this paper to show the contribution of the paper to the topic of newly optimization techniques. Despite many of the optimization techniques, which use nature for their inspiration, in this algorithm, human behavior is used as the main source of inspiration. The behaviors which are modeled through the following steps:

(1) *Initialization:* Creating initial individuals and spreading among the field is the main role of this step.
(2) *Education:* in this step, every individual tries to improve himself by learning from the best individual of its field, which is called expert individual. This process is modeled by a kid of moving around the expert individual.
(3) *Consultation:* find a random advisor and consulting with him is the main role of this step. In the consultation process, the advisor changes some variables of the individual.
(4) *Field changing:* the field of some individuals may change in this step. For this change a kind of rank probability method is used.
(5) *Finalization:* the algorithm in this step is finalized. Function values of the individuals are updated, and if the stopping criteria is reached, the algorithm will be terminated, otherwise, will go to step 2.

These steps form the HBBO optimization approach. As HBBO education and consultation process have continuous and discrete nature, respectively, this algorithm is suitable for relay coordination problem which is a mixed continuous and discrete optimization problem.

5. Test results

5.1. Nine-bus test system

In order to test the proposed approach and comparing its results with the previous approaches, at first 9-bus test systems is selected. The 9-bus system, which consists of six lines, three transformers, and three generators, is shown in Fig. 5. The system data for 9-bus test system are given in Appendix. The nominal and short circuit currents for 9-bus test system relays are listed in Tables 2 and 3. These are calculated using DIgSILENT software. The GA parameters are given in Table 4. To find the parameters of the OF, the process of trial and error has been performed and suitable parameters found as shown in Table 5. By applying GA to the OF of the nine-bus system, the results are obtained. In order to show the privilege of the proposed new OF, the results are compared with the previous OF described in [15]. In addition, to show the effect of considering variable pickup currents, two different conditions are studied. The results are discussed for three different cases:

Case 1:	Old OF considering fixed pickup current factors ($I_{pf} = 1.2$) as proposed in [15]
Case 2:	New OF and considering fixed pickup current factors ($I_{pf} = 1.2$)
Case 3:	New OF and considering variable pickup current factors with the same parameters as the case 2 (suitable case)

In all above conditions, the *TSMs* are continuous and change from 0.05 to 2. The I_{pf}-s are continuous and change from 1.2 to 1.3 and the characteristics of the relays are chosen using Table 1. The *CTI* values are considered to be 0.2. The distance relays operation times for the first, second and third zones are 20(ms), 0.3(s) and 0.6(s), respectively.

Optimal *TSMs*, I_{pf}-s, and relay characteristics, selected by the GA, are given in Table 6. In addition, the GA outputs of discrimination time values for each fault location are given in Table 7.

As it can be seen from Table 7, in case 2 and case 3 (suitable case), because of considering a large amplification factor, the miscoordinations decrease a lot. For the first fault location (F_1), the positive discrimination times are significantly minimized. Approximately all the discrimination times are zero. The average values for F_1 and F_2 fault locations in case 3 are better than case 2 and these two cases are better than case 1. The average values for the positive discrimination times in F_3 and F_4 fault locations is better

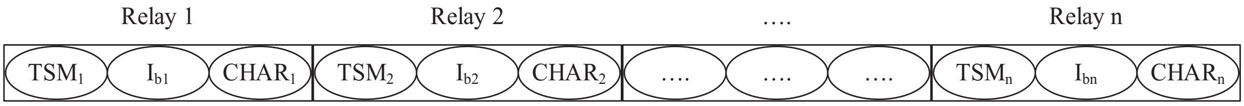


Fig. 4. Structure of chromosome.

Table 2
Nominal currents (A).

Relay number	Nominal current (A)	Relay number	Nominal current (A)	Relay number	Nominal current (A)
1	186.9	5	154.3	9	114.8
2	189.4	6	151.1	10	141.5
3	84.5	7	86.1	11	214.5
4	59.3	8	75.2	12	212.9

Table 3
Short circuit currents for main and backup relays.

Main OC & Dis	Backup OC & Dis	Main Relay SCC Fault at F1 (A)	Backup Relay SCC Fault at F1 (A)	Main Relay SCC Fault at F2 (A)	Backup Relay SCC Fault at F2 (A)	Backup Relay SCC Fault at F3 (A)	Backup Relay SCC Fault at F4 (A)	Main Relay SCC Fault at F5 (A)
1	11	2310	650	1390	332	650	380	1741
2	4	1066	1066	770	770	1066	822	905
3	1	1389	1389	853	853	1390	933	1072
4	6	1918	630	1066	281	630	332	1381
5	3	2144	853	849	245	853	317	1238
6	8	1297	1297	630	630	1297	721	880
7	5	849	849	589	589	849	638	711
8	10	2465	654	1297	277	654	325	1707
9	7	2399	589	1327	260	589	304	1715
10	12	929	929	654	654	929	704	781.2
11	9	1328	1328	649	649	1328	745	909
12	2	2434	770	929	178	770	248	1367

Table 4
GA parameters for nine-bus.

GA parameters	Value
No. function evaluation	400,000
Number of generation	4000
Size of population	100
Mutation	Adaptive feasible
Crossover	Scattered

in case 1, but the number of miscoordinations is worse than cases 2 and 3. The miscoordinations in cases 2 and 3 is only one for (12,2), while there are five miscoordinations in case 1 as highlighted in the Table 7.

In addition, it can be seen in Table 7 that in case 3 by considering pickup current factors as variables, the coordination is improved. The average values of the positive discrimination times are better for all fault locations.

By comparing case 1 with cases 2 and 3, it can be seen that the new OF is much better than the old one in decreasing the miscoordinations. The total number of miscoordinations for cases 2 and 3 is only one, while this is five for case 1. In addition, by comparing case 2 with case 3, it can be seen that by considering pickup current factors as variables, the coordination is improved and the average values of the positive discrimination times are decreased for all fault locations.

Same simulation is carried out by applying HBBO to the problem. For example for optimizing the first case, the HBBO parameters are given in Table 8. It should be noted that in comparing the results of optimization algorithm, the equivalence of number of function evaluation is an important parameter. Number of function evaluation means that how many times the algorithm calculates the OF and uses it. The number of iterations to reach optimal solution cannot show the powerfulness of the optimization algorithm, because it may calculate the OF more than one time in each iteration, as HBBO in advanced mode evaluate two times the OF in each iteration and for each of the population. More discussion about the importance of number of function evaluation can be found in [19].

Table 5
OF parameters.

Case No.	α	$\beta1,\beta2,\beta3,\beta4,\beta5$	$\beta6$	$\gamma1,\gamma2$
Case 1	1	2	2	–
Case 2	2	1	–	5
Case 3	2	1	–	5

Optimal *TSMs*, I_{pf}-s, and relay characteristics, selected by the HBBO, are given in Table 9. In addition, the HBBO outputs of discrimination time values for each fault location are given in Table 10.

By comparing the results of Tables 7 and 10, it is shown that the HBBO has better performance in the problem. In case 1, GA has more miscoordinations than HBBO. In addition, in this case, the average of positive discrimination time values for HBBO is noticeably lower than GA output. In case 2, number of miscoordinations is same but the HBBO average of positive discrimination time values are remarkably lower than GA output. In case 3, the HBBO outputs can show better, the effectiveness of the considering pickup current in the relay coordination problem. As shown in the results, the average of positive values is considerably better in HBBO than GA. These results show the effectiveness of applying better optimization algorithm on achieving better relay coordination. In the next subsection, HBBO is applied to 39-bus test system to show the effectiveness of the proposed approach compared with the previous approach in a larger power network.

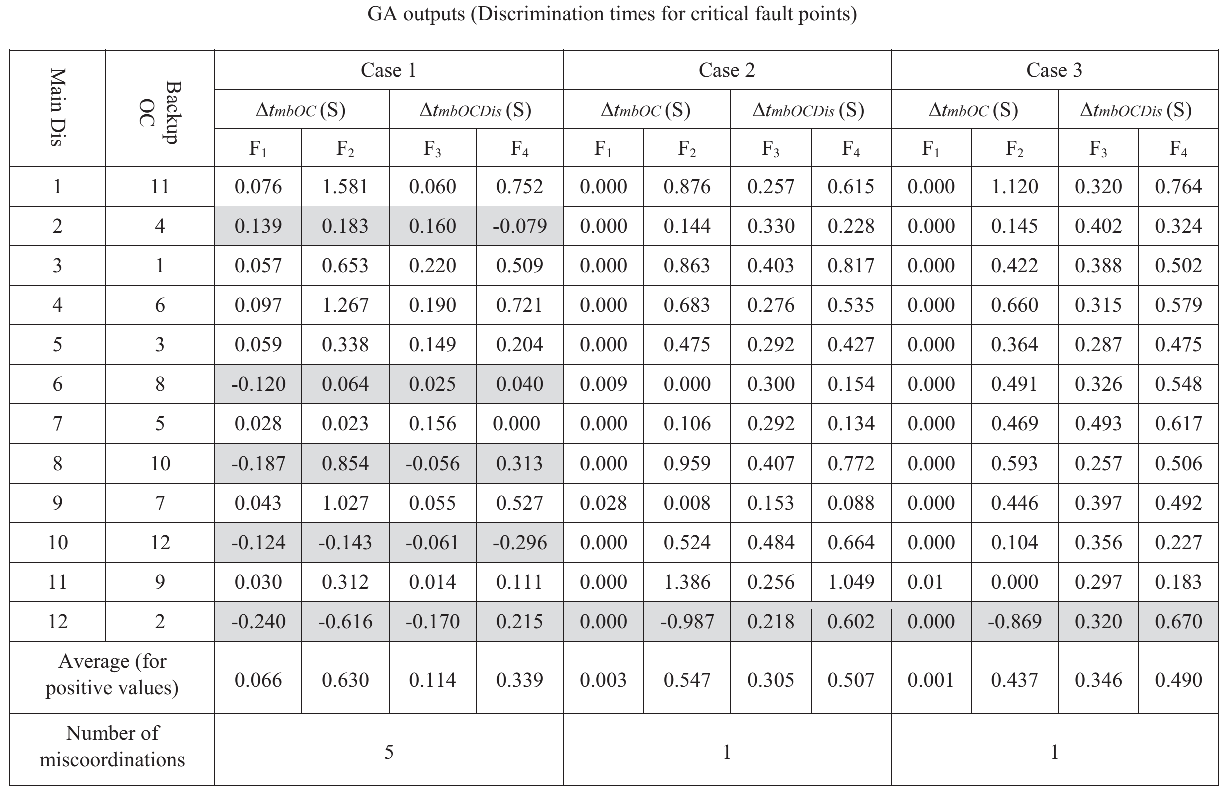
5.2. 39-bus test system

In order to show that the proposed approach is general and can be applied in each test system, it is tested on 39-bus network as another test system. The 39-bus system consists of 34 lines, 12 transformers and 10 generators which is shown in Fig. 6. The system data for 39-bus test system are given in Appendix. The nominal and short circuit currents are calculated using DIgSILENT software, which are not shown because of large amount of data. The results are investigated in three cases as same as nine-bus system study. In this test system, HBBO is used in optimizing the relay coordination of 39-bus test system to show the effectiveness of the proposed approach compared with the previous approach in

Table 6
GA outputs (*TSMs*, I_{ps}-s and Characteristic numbers).

Relay number	*TSMs*			*Ipf*	CHAR No.		
	Case 1	Case 2	Case 3	Case 3	Case 1	Case 2	Case 3
1	0.20	0.71	0.23	1.21	4	8	3
2	0.05	0.20	0.09	1.25	1	6	2
3	0.66	0.39	0.15	1.25	1	6	2
4	0.86	0.57	0.64	1.20	1	3	3
5	0.47	0.64	0.48	1.21	1	1	7
6	0.07	0.51	0.25	1.20	3	1	6
7	0.27	0.24	0.38	1.26	8	6	6
8	0.94	0.49	0.06	1.24	8	6	5
9	0.54	0.55	0.42	1.22	8	4	6
10	0.07	0.31	0.53	1.20	8	6	1
11	0.05	0.17	0.19	1.20	8	6	6
12	0.17	0.34	0.28	1.20	1	7	6
Average	0.36	0.4	0.30	1.22	–	–	–

Table 7
GA outputs (Discrimination times for critical fault points).



GA outputs (Discrimination times for critical fault points)

Main Dis	Backup OC	Case 1				Case 2				Case 3			
		Δt_{mbOC} (S)		$\Delta t_{mbOCDis}$ (S)		Δt_{mbOC} (S)		$\Delta t_{mbOCDis}$ (S)		Δt_{mbOC} (S)		$\Delta t_{mbOCDis}$ (S)	
		F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
1	11	0.076	1.581	0.060	0.752	0.000	0.876	0.257	0.615	0.000	1.120	0.320	0.764
2	4	0.139	0.183	0.160	-0.079	0.000	0.144	0.330	0.228	0.000	0.145	0.402	0.324
3	1	0.057	0.653	0.220	0.509	0.000	0.863	0.403	0.817	0.000	0.422	0.388	0.502
4	6	0.097	1.267	0.190	0.721	0.000	0.683	0.276	0.535	0.000	0.660	0.315	0.579
5	3	0.059	0.338	0.149	0.204	0.000	0.475	0.292	0.427	0.000	0.364	0.287	0.475
6	8	-0.120	0.064	0.025	0.040	0.009	0.000	0.300	0.154	0.000	0.491	0.326	0.548
7	5	0.028	0.023	0.156	0.000	0.000	0.106	0.292	0.134	0.000	0.469	0.493	0.617
8	10	-0.187	0.854	-0.056	0.313	0.000	0.959	0.407	0.772	0.000	0.593	0.257	0.506
9	7	0.043	1.027	0.055	0.527	0.028	0.008	0.153	0.088	0.000	0.446	0.397	0.492
10	12	-0.124	-0.143	-0.061	-0.296	0.000	0.524	0.484	0.664	0.000	0.104	0.356	0.227
11	9	0.030	0.312	0.014	0.111	0.000	1.386	0.256	1.049	0.01	0.000	0.297	0.183
12	2	-0.240	-0.616	-0.170	0.215	0.000	-0.987	0.218	0.602	0.000	-0.869	0.320	0.670
Average (for positive values)		0.066	0.630	0.114	0.339	0.003	0.547	0.305	0.507	0.001	0.437	0.346	0.490
Number of miscoordinations		5				1				1			

Table 8
HBBO parameters.

HBBO parameters	Value
No. function evaluation	400,000
nIteration	400
Population size	500
nField	100
K1	0
K2	2.5
σ	0.2
Mode	Advanced

a larger power network. In addition to previous three cases, a new case is studied in this test system. Some transmission utilities may tend to use same characteristics for the overcurrent relays. In case 4, the characteristics of the overcurrent relays are assumed to be fixed as moderately inverse (ANSI/IEEE standard) and the proposed OF is applied to select optimal pickup current and *TSMs* of the relays.

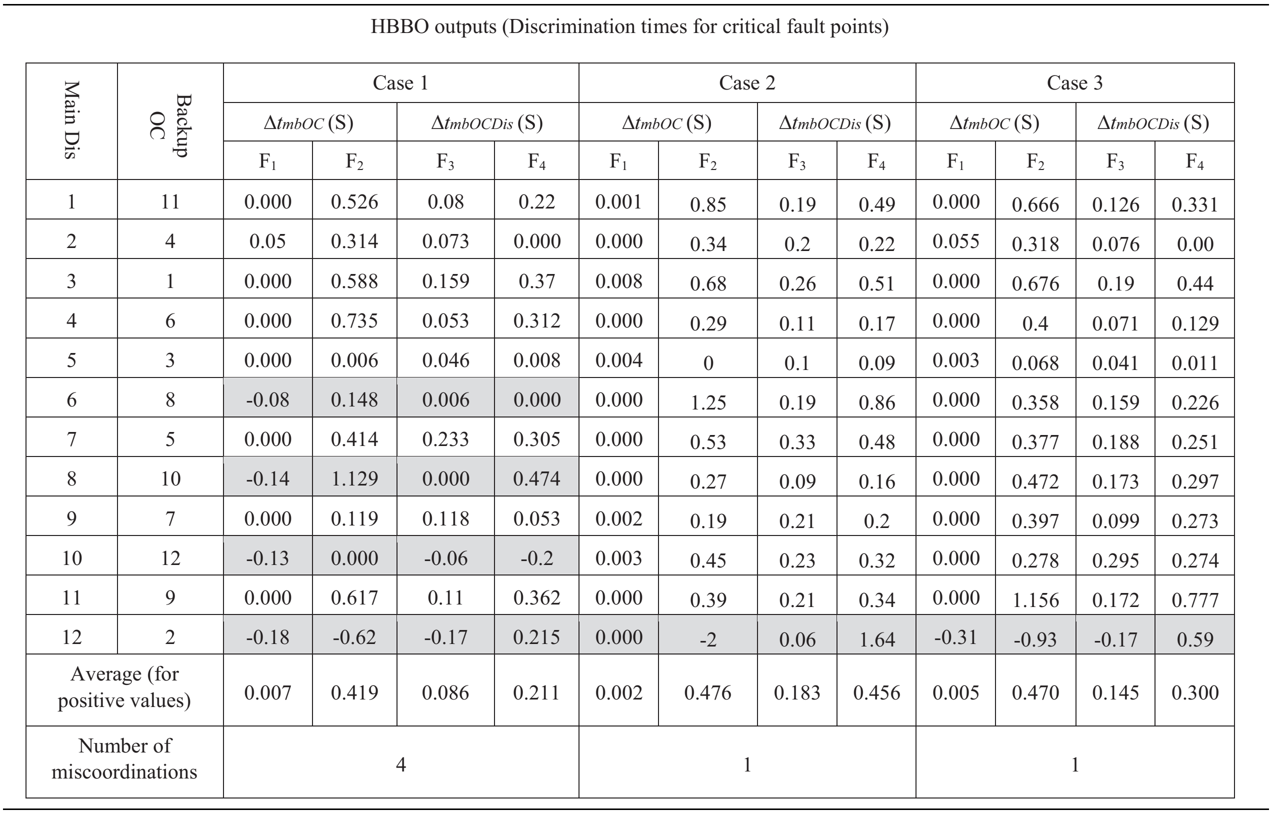
The summary of the discrimination times, selected by the HBBO, are given in Table 11.

As it can be seen in Table 11, the old approach focuses on reducing the discrimination times and the number of miscoordinations is not considered in that. However, the proposed approach consider the miscoordination and discrimination time simultaneously. In other words, in the old approach it is only important to have lower discrimination time even with high miscoordination which is not practical in the power system, while the proposed approach consider both of them, miscoordination and lower discrimination time, which is more useful in the real world.

Table 9
HBBO outputs (*TSMs*, I_{ps}-s and Characteristic numbers).

Relay number	*TSMs*			*Ipf*	CHAR No.		
	Case 1	Case 2	Case 3	Case 3	Case 1	Case 2	Case 3
1	0.18	0.54	0.53	1.21	4	8	8
2	0.05	0.1	0.13	1.25	1	6	6
3	0.46	0.25	0.249	1.25	1	6	6
4	0.82	1.19	1.18	1.20	4	4	4
5	0.11	0.36	0.358	1.21	4	8	8
6	0.05	0.15	0.15	1.20	3	6	6
7	0.49	0.61	0.61	1.26	1	1	1
8	0.87	1.06	1.06	1.24	8	4	4
9	0.77	0.28	0.27	1.22	8	3	3
10	0.09	0.35	0.35	1.20	8	1	1
11	0.23	0.3	0.3	1.20	1	1	1
12	0.07	0.19	0.184	1.20	8	8	8
Average	0.35	0.45	0.44	1.22	–	–	–

Table 10
HBBO outputs (Discrimination times for critical fault points).



HBBO outputs (Discrimination times for critical fault points)

Main Dis	Backup OC	Case 1				Case 2				Case 3			
		Δt_{mbOC} (S)		$\Delta t_{mbOCDis}$ (S)		Δt_{mbOC} (S)		$\Delta t_{mbOCDis}$ (S)		Δt_{mbOC} (S)		$\Delta t_{mbOCDis}$ (S)	
		F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
1	11	0.000	0.526	0.08	0.22	0.001	0.85	0.19	0.49	0.000	0.666	0.126	0.331
2	4	0.05	0.314	0.073	0.000	0.000	0.34	0.2	0.22	0.055	0.318	0.076	0.00
3	1	0.000	0.588	0.159	0.37	0.008	0.68	0.26	0.51	0.000	0.676	0.19	0.44
4	6	0.000	0.735	0.053	0.312	0.000	0.29	0.11	0.17	0.000	0.4	0.071	0.129
5	3	0.000	0.006	0.046	0.008	0.004	0	0.1	0.09	0.003	0.068	0.041	0.011
6	8	-0.08	0.148	0.006	0.000	0.000	1.25	0.19	0.86	0.000	0.358	0.159	0.226
7	5	0.000	0.414	0.233	0.305	0.000	0.53	0.33	0.48	0.000	0.377	0.188	0.251
8	10	-0.14	1.129	0.000	0.474	0.000	0.27	0.09	0.16	0.000	0.472	0.173	0.297
9	7	0.000	0.119	0.118	0.053	0.002	0.19	0.21	0.2	0.000	0.397	0.099	0.273
10	12	-0.13	0.000	-0.06	-0.2	0.003	0.45	0.23	0.32	0.000	0.278	0.295	0.274
11	9	0.000	0.617	0.11	0.362	0.000	0.39	0.21	0.34	0.000	1.156	0.172	0.777
12	2	-0.18	-0.62	-0.17	0.215	0.000	-2	0.06	1.64	-0.31	-0.93	-0.17	0.59
Average (for positive values)		0.007	0.419	0.086	0.211	0.002	0.476	0.183	0.456	0.005	0.470	0.145	0.300
Number of miscoordinations		4				1				1			

Table 11
Summary of discrimination times for HBBO outputs.

Δt	Case 1 Average of positive values (S)	Case 2 Average of positive values (S)	Case 3 Average of positive values (S)	Case 4 Average of positive values (S)
$\Delta tmbOC, F_1$	0.046	0.1921	0.1551	0.2186
$\Delta tmbOC, F_2$	0.486	0.8449	0.9139	0.7847
$\Delta tmbOCDis, F_3$	0.101	0.4765	0.4364	1.2677
$\Delta tmbOCDis, F_4$	0.256	0.8682	0.9100	1.9409
Total	0.8951	2.3817	2.4154	4.2118
No. of miscoordination	59	17	14	17

In addition, considering the pickup current in the large system, not only can reduce the number of miscoordination, but also reduce the total discrimination times. In other words, considering selection of optimal pickup current can be useful to better coordinate the power system protection, especially in large interconnected systems. In the previous network, 9-bus system, the effect of pickup current was not obvious in reduction of number of miscoordination due to the size of the understudy system and it only

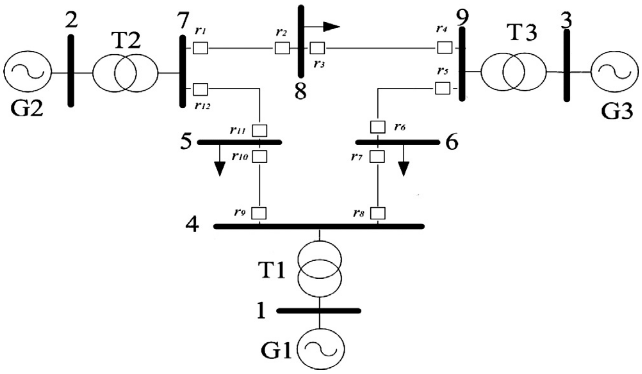


Fig. 5. 9-bus test system.

Table 12
9-bus line information.

From Bus	To Bus	R (Ω)	X (Ω)
1	4	0	0.0576
2	7	0	0.0625
3	9	0	0.0586
4	5	0.0101	0.085
5	7	0.032	0.161
6	4	0.017	0.092
7	8	0.0085	0.072
8	9	0.0119	0.1004
9	6	0.039	0.170

affects the discrimination times. This effect is seen in the 39-bus system.

As shown in Table 11, optimal characteristics selection of the overcurrent relays can reduce number of miscoordination, in addition to discrimination times. By comparison of case 3 with case 4, it can be seen that the average of positive discrimination times is obviously better by relay characteristics selection and number of miscoordinations is reduced. In addition, as shown in the results of cases 2 and 4, it can be concluded that relays coordination considering different relays characteristics with fixed pickup currents can be conducted better, compared with condition that fixed relays characteristics with variable pickup current is investigated.

As shown in the results, proposed approach can reduce miscoordination compared with the previous approaches and improve average of positive discrimination times by considering optimal selection of pickup current in the OF. Structure of distribution systems are changing from natural form of radial structure to a looped and meshed network due to the increasing interest in smart grids. Protection setting of smart grids depends on its connection situation, islanding or grid-connected modes. Fault currents of each mode are different and should be considered in protection relay settings. The settings are determined according to power system condition, which should be monitored in real-time. The approach

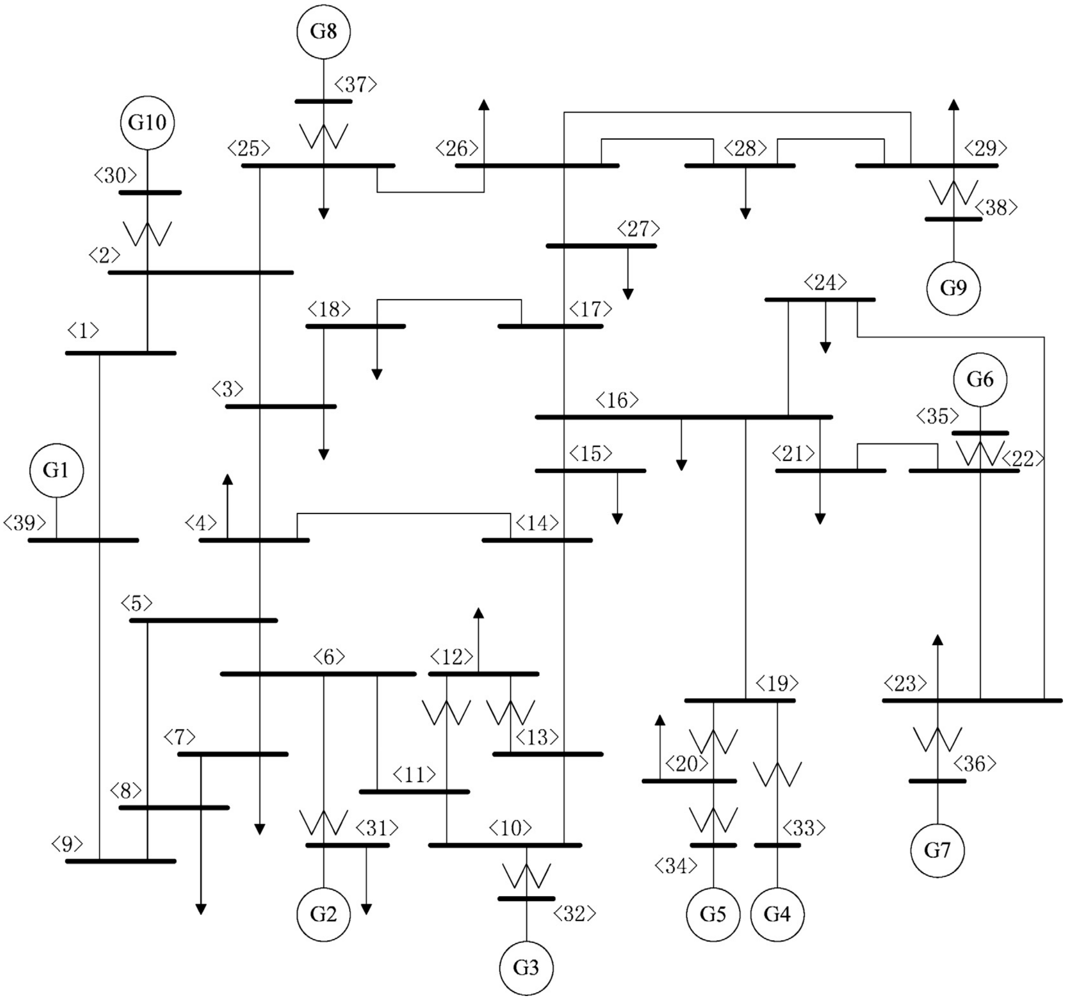


Fig. 6. 39-bus test system.

Table 13
39-bus line information.

From Bus	To Bus	R (Ω)	X (Ω)
1	2	0.0035	0.0411
1	39	0.001	0.025
2	3	0.0013	0.0151
2	25	0.007	0.0086
3	4	0.0013	0.0213
3	18	0.0011	0.0133
4	5	0.0008	0.0128
4	14	0.0008	0.0129
5	6	0.0002	0.0026
5	8	0.0008	0.0112
6	7	0.0006	0.0092
6	11	0.0007	0.0082
7	8	0.0004	0.0046
8	9	0.0023	0.0363
9	39	0.001	0.025
10	11	0.0004	0.0043
10	13	0.0004	0.0043
13	14	0.0009	0.0101
14	15	0.0018	0.0217
15	16	0.0009	0.0094
16	17	0.0007	0.0089
16	19	0.0016	0.0195
16	21	0.0008	0.0135
16	24	0.0003	0.0059
17	18	0.0007	0.0082
17	27	0.0013	0.0173
21	22	0.0008	0.014
22	23	0.0006	0.0096
23	24	0.0022	0.035
25	26	0.0032	0.0323
26	27	0.0014	0.0147
26	28	0.0043	0.0474
26	29	0.0057	0.0625
28	29	0.0014	0.0151
12	11	0.0016	0.0435
12	13	0.0016	0.0435
6	31	0	0.025
10	32	0	0.02
19	33	0.0007	0.0142
20	34	0.0009	0.018
22	35	0	0.0143
23	36	0.0005	0.0272
25	37	0.0006	0.0232
2	30	0	0.0181
29	38	0.0008	0.0156
19	20	0.0007	0.0138

presented in this paper can be applied to smart grids and use real-time data to update relay settings. The proposed approach can be useful in the power system to overcome miscoordination problem of relay coordination, in addition to reducing discrimination times.

It should be noted that in smart grids, penetration of DGs is increasing due to different benefits of them for distribution networks such as power quality improvement and reliability of the system. Beside valuable advantages that using DGs brings for the power system, they have a high impact on protection system. In order to solve the protection problem caused by DGs, different methods to determine new TSMs and pickup currents have been presented in the literature which are categorized in adaptive protection methods [20,21], and are under development and study. The fault currents of the system change in the presence of the DGs. Therefore, we are facing a new system structure for protection. In order to explain a simple way to overcome protection problem of the system incorporating DGs, the fault currents of this new system should be calculated and used to update TSMs and pickup currents for all the relays. Therefore, our method presented in this paper can be applicable to solve protection problem for the systems incorporate with DGs by just calculating system real-time fault currents, which is needed in Eq. (14) and the objective function does not need to be changed.

6. Conclusion

A new approach has been developed and the GA and HBBO have been used to solve the coordination problem of the combined directional overcurrent and distance relays. Previous approaches could not find a solution to avoid the miscoordinations and also, optimal selection of pickup current has not been investigated. In the proposed approach, the miscoordination problems have been solved and also the coordination has been improved. Various directional overcurrent relays characteristics and also, different pickup currents have been considered in the optimization process to find the best of them. The proposed OF has been tested on a 9-bus sample system and the results of applying HBBO and GA have been compared. It has been shown that by using proposed OF, the miscoordinations decreased and the relay coordination has been improved. In addition, the pickup current effect on reduction of discrimination times has been discussed. The proposed approach has been tested on 39-bus test system as larger and more complex system to show better, the advantages of the proposed approach than the previous ones. In the understudy large system, not only the effect of proposed approach on reducing number of miscoordination has been shown, but also the pickup current effect on reduction of number of miscoordinations and discrimination times has been discussed. Overall, the simulation studies have been shown the privilege of the proposed OF compared with previous works, in coordination of combine distance and directional overcurrent relays.

Appendix A

Sample system information is listed in Tables 9 and 10. This system is shown in Fig. 5 (see Tables 12 and 13).

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