Optimal Combined Overcurrent and Distance Relays Coordination Incorporating Intelligent Overcurrent Relays Characteristic Selection

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***Abstract*—In this paper, a new objective function (OF) within the genetic algorithm (GA) approach is presented to solve the optimization problem of coordination of overcurrent and distance relays. The existing objective function of overcurrent (O/C) relays coordination is improved and extended to include the coordination of O/C and distance relays. Various O/C relays characteristics are considered within the approach to select the best of them by GA to fulfill optimal coordination. The proposed method is applied to two different power system networks. Simulation results demonstrate that the method can obtain feasible and effective solutions for optimal coordination in the practical power system networks.**

***Index Terms*—Distance relay, genetic algorithm (GA), O/C relay, optimal coordination, relay characteristics.**

I. INTRODUCTION

OVERCURRENT and distance relays are mostly used for transmission and subtransmission protection systems [1]. In other words, two types of protection schemes are used: 1) two similar distance relays, namely main 1 and main 2, at each line; the scheme is normally used in important transmission systems and 2) a distance protection plus O/C protection. This scheme is used almost for subtransmission systems and in some transmission systems. To consider comprehensive coordination, a distance relay with a distance one, an O/C relay with an O/C one, and, finally, an O/C relay with a distance one, must be coordinated when one of them is considered to be the main relay and the other is the backup.

For O/C relays, the optimal coordination has been performed using linear programming techniques, including simplex [2]; two-phase simplex [3]; and dual simplex [4] methods. In [6], the optimal solution is made by constraints only. The disadvantage of this method is that if the constraints are not fulfilled, we do not have an optimal solution. In intelligent optimization methods, the constraints are included in an objective function (OF) [5], [7], and [8]. The optimal coordination in [7] has been performed by a method based on GA. In [8], the optimal coordination has been performed by a method based on particle swarm optimization (PSO) while in [9], the same has been done by using an evolutionary algorithm. The coordination made in these methods has two problems. One is miscoordination and the other poses the lack of solution for relays with both discrete and continuous time setting multipliers (TSMs). In [5], the mentioned problems have been solved. The existing GA is improved by adding a new expression to the OF, so that the miscoordination problems are solved. The coordination algorithm can also handle continuous and discrete TSMs.

It should be noted that all of the aforementioned optimal coordination by GA (as in [5] and [7]) has been done for O/C relays only. However, in transmission and subtransmission systems, the coordination of O/C and distance relays should be considered. On the other hand, in all mentioned references, O/C relay characteristics have been considered to be fixed while in digital relays, different O/C relay characteristics can be selected. Therefore, the coordination algorithm should have the capability of selecting the best characteristic for O/C relays to have the optimal solution.

In [1] and [10], the optimal coordination has been performed by the linear programming technique to find TSM settings of relays. In linear programming techniques, it is not possible to select O/C relays characteristic addition to relays TSM to have the optimal coordination.

In the cases of O/C-O/C and O/C-distance relays coordination which are used in this paper, it is necessary to find the critical fault locations. The critical fault locations are the points the faults are considered to be on. These points are the fault points on which the discrimination time (Δt) between the backup and main relays is caused to be minimum. The coordination is made based on the constraints derived from the values of Δt for critical fault locations.

In this paper, the problem of optimal coordination of O/C relays in a mixed protection scheme with distance relays formulated in [11] has been modified in such a way that five different critical points as the fault position are taken into account while in the mentioned references, only three or four critical points have been considered. Furthermore, to make the optimal method flexible, the method has been applied to two different transmission and subtransmission power system networks with different configurations. Also, regarding the protection system flexibility, the

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method is capable of handling and choosing the best characteristic for each O/C to obtain the optimal combined coordination of distance and O/C relay for the critical fault locations.

II. Review of Recent Optimal Relay Coordination

This section is devoted to review the notation and concept of GA application to optimal relays coordination presented in [5], and the coordination method used in [1] to give a better understanding and coherency to this paper.

The flow diagram of the GA application to O/C relay coordination is shown in Appendix A. Although the coordination of O/C and distance relays are made in this paper, the similar GA procedure of [5] is used. Also, the chromosomes of relative O/C relays are modified which will be described in Section IV. Therefore, the summary of the procedure is given here.

The TSMs, with respect to the number of relays, are considered as the genomes of the chromosomes in GA. In other words, some TSMs sets, that is, (TSM1, TSM2, TSM3, …, TSMn), (TSM’1, TSM’2, TSM’3, …, TSM’n), … belonging to relay set (R1, R2, R3, …, Rn) are initially randomly selected [5].

To evaluate the goodness of each chromosome, it is essential to define an OF. The OF introduced in [5] is as follows:

$$\mathrm{OF} = \alpha_1 \sum (t_i)^2 + \alpha_2 \sum \left(\Delta t_{\mathrm{mb}} - \beta_2 \left(\Delta t_{\mathrm{mb}} - |\Delta t_{\mathrm{mb}}|\right)\right)^2 . \tag{1}$$

The first term of (1) is the sum of O/C relays’ operating time and the second term is the coordination constraint. $\alpha_1, \alpha_2, \beta_2$ are the weighting factors; t_i is the operating time of O/C relays; and Δt_{mb} is the discrimination between the main and backup O/C relays.

After each iteration, the new TSMs sets belonging to relays R1 to Rn are given to the algorithm. The process is terminated when the number of iterations becomes equal to the generation size [5].

In [1], the coordination between the O/C and second zone distance relay has been made using the linear programming technique. The fault point by which relative discrimination times between O/C and distance relays are checked is the starting point of the second zone. In this regard, two problems should be considered. Another fault point being just close to the C. B of the main relay, in addition to the considered point plus using the intelligent method instead of linear programming technique, will be described in the next section.

Although the fault cases where the O/C relays operating for a z2-faults faster than the distance relays are rare, to prevent the operating times of relevant O/C relays become too long, the optimal coordination between the O/C and second zone distance relay is necessary. In other words, to have suitable backup protection, there is a need to have optimal coordination of O/C and second zone distance relays. Also, this justification is true for the fault close to the C.B of the main relays and fault in the end of the distance relay second zone.

III. Problem Statement

As mentioned in Section I, the existing intelligent methods, such as GA and the existing mathematical methods including linear programming techniques, cannot solve some important problems. The detailed description of these problems is as follows.

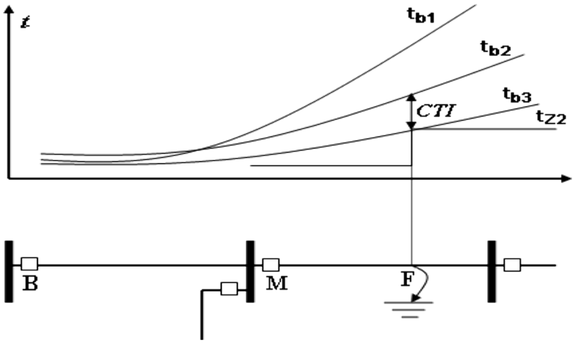

Fig. 1. Various characteristics in coordination between overcurrent and distance relays.

1) In all existing intelligent and mathematical coordination methods, the fixed characteristic has been applied for all O/C relays, while in power networks, there are many real digital O/C relays which have the flexibility of having various characteristics. Therefore, there is a need to have a method that is able to select the best characteristic for O/C relays to achieve the optimal coordination. To clarify this problem, we can refer to Fig. 1. In this figure, an O/C relay is located at B and the distance one at M. The O/C relay is the backup of the distance relay. When a fault occurs at F, which will be defined as one of the critical points in the later section, the discrimination time between the operating time of the O/C relay and the second zone of distance relay is minimum. If only one choice (i.e., characteristic b_3) exists, the discrimination time between the backup O/C relay and the main distance relay will be less than CTI (coordination time interval) and causes miscoordination. Now, if characteristic b_1 exists instead of b_3, having a long fault clearing time of the backup O/C relay will be the problem. In other words, instead of characteristics b_1 and b_3, b_2, which is between, is more suitable. Therefore, the development of an approach to have the flexibility of selecting the suitable characteristic is a vital job.
2) It is necessary to find a solution to avoid having large discrimination times extra to coordination. This will be accomplished in this paper as a novelty by developing a new OF which will be described in Section IV.
3) In some previous papers, the coordination of distance and O/C relay has been accomplished by using the linear programming technique. This technique, like other mathematical methods, has limitations and cannot be used for solving two previously mentioned problems. However, intelligent methods such as GA, which is used in this paper, can be used for nonlinear problems.
4) The critical fault points on which the discrimination times have minimum values are five specific points. Four of them have been considered in [1]. The fault just close to the CB of the main relay, which has not been considered in [1], must be taken into account. This will be described in the next section.

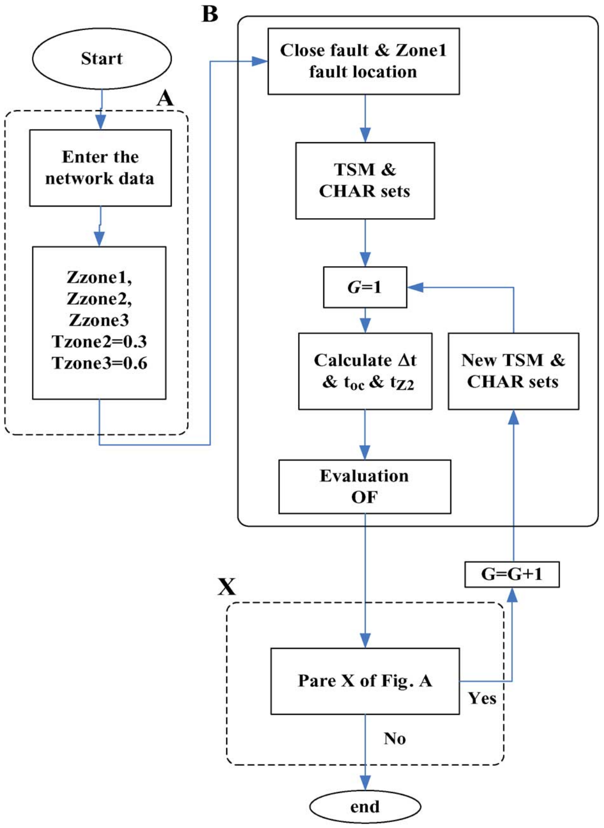

Fig. 2. Flowchart of the new method.

R1		R2		R3		…		Rn	
TSM1	CHAR1	TSM2	CHAR2	TSM3	CHAR3	…	…	TSM n	CHARn

Fig. 3. Structure of chromosome.

IV. Proposed Method

To fulfill the four problems described in Section III, a new method based on GA has been developed. The flow diagram of the new method is shown in Fig. 2. It is assumed that the coordination of distance with distance relay is made separately, and the results are available. Part A is not new; it is given in [1]. Part X of Fig. 9 in Appendix A is exactly repeated. Part B of the flow diagram is the novelty of this paper. At first, after entering the network data, the impedances and the time settings of the three zones of distance relays are calculated.

Five fault points, which will be described later in this section, are considered. Considering a close fault extra to the beginning of zone 2 and including related operating discrimination times of O/C and distance coordination in OF is one of the novelties of this paper. After that, GA will start.

The key variable in the GA is the chromosome and consists of all relay TSMs and all relay characteristics. In other words, some TSMs and characteristic sets, that is, (TSM1, TSM2, TSM3, …, TSMn, CHAR1, CHAR2, CHAR3, …, CHARn), (TSM'1, TSM'2, TSM'3, …, TSM'n, CHAR'1, CHAR'2, CHAR'3, …, CHAR'n), … belonging to relay set (R1, R2, R3, …, Rn) are initially randomly selected. The structure of the chromosome in this paper is shown in Fig. 3. As can be seen, considering both TSMs and relays characteristics is the second novelty compared to [1] and [5].

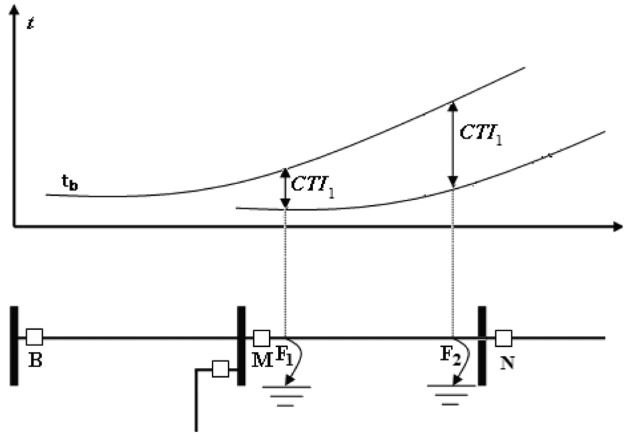

Fig. 4. Critical fault locations for the coordination between P/B overcurrent relays.

The third novelty is new OF development. The new OF consists of the terms related to combined O/C and distance relays coordination. The contents of OF are extracted from the following descriptions.

In interconnected networks, all distance and O/C relays can be backup protection for other O/C or distance relays. Four different coordination processes containing distance-distance, O/C-O/C, O/C-distance, and distance-O/C should be fulfilled. Distance-distance relays coordination should be done before the optimization process to calculate the impedance settings for three different zones of distance relays. In the next step, these settings are used in the optimization algorithm for the coordination of overcurrent and distance relays. Therefore, TSMs of all O/C relays and the operating time of the second zone of all distance relays must be determined for critical conditions.

As mentioned before, the critical conditions for O/C-O/C relays coordination (The O/C relay is backup of O/C relay) are shown in Fig. 4. The discrimination times between the operating times of relays for faults occuring at F_1 (near end fault) and F_2 (far end fault), should be checked as follows:

$$t_b(F_1) - t_m(F_1) \geq CTI_1 \tag{2}$$

$$t_b(F_2) - t_m(F_2) \geq CTI_1 \tag{3}$$

where $t_b(F_i)$ and $t_m(F_i)$ are the operating times of the main and backup O/C relays, respectively, at critical point F_i, and CTI_1 is the coordination time interval for O/C-O/C relays coordination. $t_b(F_1)$ and $t_b(F_2)$ depend on the characteristic type of the O/C relay selected by GA.

In O/C-distance coordination, the O/C relay is the backup of the distance relay. The critical points are shown in Fig. 5. When faults occur at F_3 and F_4, the discrimination times between the operating time of the O/C relay and that of the distance one are minimum. Therefore, the following expressions must be appointed at the critical fault locations F_3 and F_4:

$$t_b(F_3) - t_{Z1} \geq CTI_2 \tag{4}$$

$$t_b(F_4) - t_{Z2} \geq CTI_2. \tag{5}$$

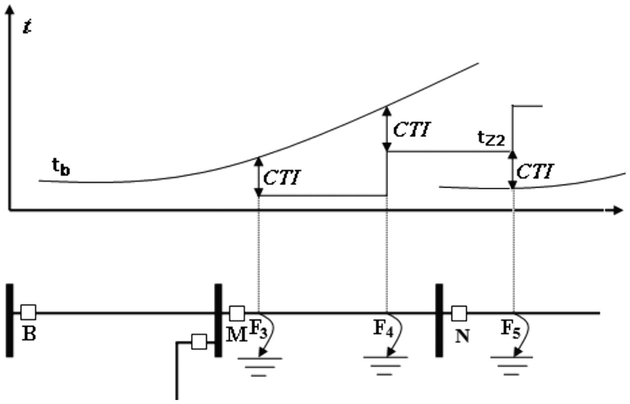

Fig. 5. Critical fault locations for the coordination between overcurrent and distance relays.

where $t_b(F_i)$ is the operating time of the O/C relay at Fi, t_{Z1} and t_{Z2} are the operating times of the first and second zone of the distance relay, and CTI_2 is the coordination time interval for O/C-distance coordination.

The other critical point seen in Fig. 5 is for distance-O/C coordination—that distance relay is the backup of the overcurrent relay

$$t_{Z2} - t_m(F_5) \geq CTI_3 \tag{6}$$

where CTI_3 is the coordination time interval for distance-O/C coordination. Other parameters are defined in the previous equations.

The fulfillment of (2) and (3) is given in the OF formula. $\mathrm{O.F}_{\mathrm{oc-oc}}$ is formulated as

$$\begin{aligned}\mathrm{O.F}_{\mathrm{oc-oc}} = &\alpha \sum_{n=1}^{N} t_n + \beta_1 \\ &\times \sum_{k_1=1}^{P_1} \left(\Delta t_{\mathrm{mbOC|F_1|}} - \left|\Delta t_{\mathrm{mbOC|F_1|}}\right|\right)^2 + \beta_1 \\ &\times \sum_{k_1=1}^{P_1} \left(\Delta t_{\mathrm{mbOC|F_2|}} - \left|\Delta t_{\mathrm{mbOC|F_2|}}\right|\right)^2 + \beta_2 \\ &\times \sum_{k_1=1}^{P_1} \left(\Delta t_{\mathrm{mbOC|F_1|}} + \left|\Delta t_{\mathrm{mbOC|F_1|}}\right|\right)^2 + \beta_3 \\ &\times \sum_{k_1=1}^{P_1} \left(\Delta t_{\mathrm{mbOC|F_2|}} + \left|\Delta t_{\mathrm{mbOC|F_2|}}\right|\right)^2. \end{aligned} \tag{7}$$

$\mathrm{O.F}_{\mathrm{oc-dis}}$ guaranties the constraints (4) and (5) that are formulated as follows:

$$\begin{aligned} O.F_{oc-dis} \\ = &\beta_1 \sum_{k_2=1}^{P_2} \left(\Delta t_{\mathrm{mbOCDIS|F_3|}} - \left|\Delta t_{\mathrm{mbOCDIS|F_3|}}\right|\right)^2 \\ &+ \beta_1 \sum_{k_2=1}^{P_2} \left(\Delta t_{\mathrm{mbOCDIS|F_4|}} - \left|\Delta t_{\mathrm{mbOCDIS|F_4|}}\right|\right)^2 \\ &+ \beta_4 \sum_{k_2=1}^{P_2} \left(\Delta t_{\mathrm{mbOCDIS|F_3|}} + \left|\Delta t_{\mathrm{mbOCDIS|F_3|}}\right|\right)^2 \\ &+ \beta_5 \sum_{k_2=1}^{P_2} \left(\Delta t_{\mathrm{mbOCDIS|F_4|}} + \left|\Delta t_{\mathrm{mbOCDIS|F_4|}}\right|\right)^2. \end{aligned} \tag{8}$$

The O.F of coordination when the distance relay is the backup of the O/C relay is as follows:

$$\mathrm{O.F}_{\mathrm{dis-oc}} = \beta_6 \times \sum_{k_3=1}^{P_3} \left(\Delta t_{\mathrm{mbDISOC}}\right). \tag{9}$$

The final OF of the genetic algorithm for O/C and distance relays coordination is obtained as follows:

$$\mathrm{O.F} = \mathrm{O.F}_{\mathrm{oc-oc}} + \mathrm{O.F}_{\mathrm{oc-dis}} + \mathrm{O.F}_{\mathrm{dis-oc}} \tag{10}$$

where $\beta_1, \ldots, \beta_5$ and β_6 are the weighting factors, k_1 is the number of main and backup O/C relays pair that changes from 1 to P_1, and k_2 is the number of main distance and backup O/C relays that changes from 1 to P_2, k_3 is the number of main O/C and backup distance relays that changes from 1 to P_3, $\Delta t_{mbOC|F_i|}$ is called the discrimination time between the main and backup O/C relays for the fault occurring at $\mathrm{F_i}$, and $\Delta t_{mbOCDIS|F_i|}$ is the discrimination time between the main distance and backup O/C relays for the fault at $\mathrm{F_i}$ which are obtained from

$$\Delta t_{\mathrm{mbOC|F_i|}} = t_{bOC|F_i|} - t_{\mathrm{mOC|F_i|}} - CTI_1 \tag{11}$$

$$\Delta t_{\mathrm{mbOCDIS|F_i|}} = t_{bOC|F_i|} - t_{\mathrm{mDIS|F_i|}} - CTI_2 \tag{12}$$

where $t_{bOC|F_i|}$ and $t_{mOC|F_i|}$ are the operating times of the main and backup O/C relay for the fault at $\mathrm{F_i}$, respectively, and $t_{mDIS|F_i|}$ is the operating time of the first zone of the main distance relay at $\mathrm{F_i}$.

$\Delta t_{mbDISOC}$ is defined as follows and used in $\mathrm{O.F}_{\mathrm{dis-oc}}$ to decrease the operating time of the second zone of the distance relay.

$$\Delta t_{\mathrm{mbDISOC}} = t_{Z2} - CTI_3 \tag{13}$$

where t_{Z2} (the operating time of the second zone of the distance relays) at each iteration of GA is obtained according to (6) as follows:

$$t_{Z2} = \max\left(\left(t_m(F_5) + CTI_3\right),\ t_z\right) \tag{14}$$

where $\mathrm{t_z}$ is the initial time delay for the second zone of the distance relay.

The second and the third terms of (7) fulfill the requirement of O/C relays coordination. In other words, these terms are similar to the second expression of the modified (1) to keep the necessary discrimination times between the main and backup O/C relays. To describe the role of these two terms, consider $\Delta t_{mbOC|F_i|}$ to be positive, then the relative term is zero; however, if $\Delta t_{mbOC|F_i|}$ is negative, the mentioned term will be $2\beta_1 \times \Delta t_{mbOC|F_i|}$ and obviously for positive values of β_1, the new terms will have large values. Then, based on a concept of the evaluation and selection parts of GA, those values that have

TABLE I
CHARACTERISTIC 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

a lower value of OF in the chromosomes are granted more opportunities to select the next iteration.

If the GA selects O/C relays with very inverse characteristics, it is probable to have large discrimination time values for critical fault locations which are not desirable. As mentioned in Section III, it is necessary to avoid having large values of discrimination times. To solve this problem, two new terms (i.e., the second and the forth terms) are added to $\mathrm{O.F_{oc-oc}}$. When $\Delta t_{mbOC|F_1|}$ or $\Delta t_{mbOC|F_2|}$ are positive and by the positive values of β_2 and β_3, these new terms will have large values and will not be selected for the next generation of GA. By choosing the best values for β_1, β_2, and β_3, having optimal coordination and logical discrimination times will be supported.

The $\mathrm{O.F_{oc-dis}}$ in (8) is related to overcurrent and distance relays coordination constraints. Similar to (7), β_1 is the weighting factor for negative values of $\Delta t_{mbOCDIS|F_i|}$ in the first and second term in (8). These terms are used in OF to satisfy constraints (4) and (5) that are related to faults in critical points $\mathrm{F_3}$ and $\mathrm{F_4}$. The following two terms in (8) are similar to the last terms in (7) and are added in $\mathrm{O.F_{oc-dis}}$ to guarantee obtaining a minimum fault clearing time for various O/C relays characteristics.

After completing the stages of part X, if the necessary requirements are not fulfilled, the new TSM and CHAR sets of relays are chosen as shown in part B. In other words, after completion of each iteration, in the feedback route after $\mathrm{G = G+1}$, new TSM and CHAR sets are selected. It should be noted that for finding the O/C relays operating times, a more common formula for approximating the relay characteristic is used [12]

$$t = \mathrm{TSM}\left(\frac{K}{M^{\alpha}-1}+L\right) \quad (15)$$

where M is the ratio of short-circuit current (I_{sc}) to the pickup current (I_b) of relay $(M = I_{sc}/I_b)$, and t is the relay operating time. K, α, L are the scalar quantities and are given in Table I. With these values of K, α, L, eight different characteristics, which are used in practice for each O/C relay, can be chosen by GA to have optimal coordination. The curves of these eight different characteristics are shown in Fig. 6. The process continues until the requirements are fulfilled.

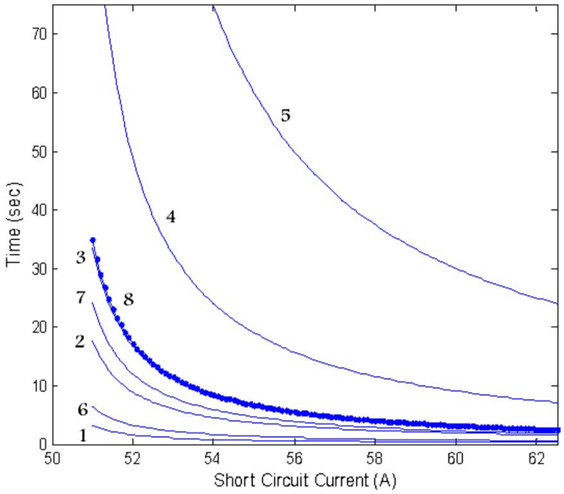

Fig. 6. Eight relay characteristics.

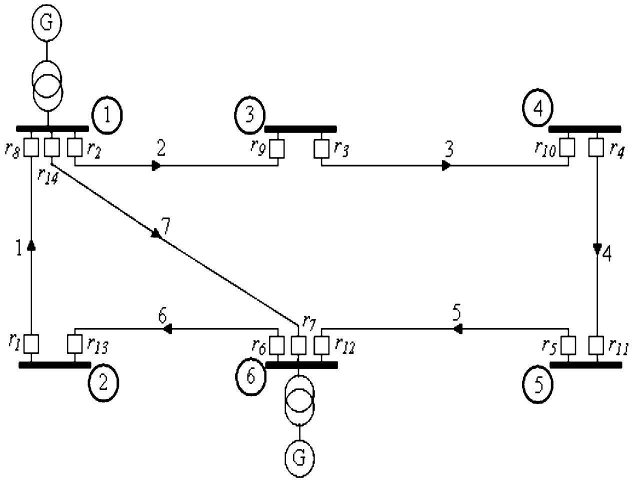

Fig. 7. Sample network.

V. TEST RESULTS

To test the method described in Section IV, two different networks, namely, sample 1 and 2 (i.e., one with six buses and the other with IEEE 30 buses) are selected.

A. Sample 1

As mentioned before, sample 1 is the six-buses network shown in Fig. 7. To analyze the results of the proposed method application to the sample network, the description is divided into two subsections named: 1) network and protection data, and 2) results and discussion, which will be given below:

1) Network and Protection Data: Fig. 7 consists of 7 lines, 6 buses, 2 transformers, and 2 generators. As shown in Fig. 2, prior to starting optimal O/C and distance relays coordination, the coordination of distance relays for all branches must be made. In this paper, for considered networks, the settings of distance relays (i.e., the impedances of first, second, and third zones plus the relative operating times) have been obtained using the method described in [13]. As will be given later, the operating

TABLE II
PICKUP CURRENT SETTINGS' DATA

Relay number	Load current	Pickup current	Relay number	Load current	Pickup current
1	104	125	8	109	137
2	166	200	9	118	135
3	125	150	10	110	137
4	180	200	11	135	162
5	129	137	12	122	137
6	114	137	13	125	150
7	141	162	14	166	200

TABLE III
SC CURRENT FOR MAIN AND BACKUP OVERCURRENT RELAYS

Main O/C & Dist	Backup O/C & Dist	Main relay SC Current Fault at F1 (A)	Backup relay SC Current-Fault at F1 (A)	Main relay SC Current Fault at F2 (A)	Backup relay SC Current-Fault at F2 (A)	Backup O/C relay SC Current-Fault at F3 (A)	Backup O/C relay SC Current-Fault at F4 (A)	Main O/C relay SC Current-Fault at F5 (A)
2	1	5428	828	3544	386	828	455	3994
14	1	4184	816	1607	816	816	488	1584
3	2	3505	3505	1789	1789	3505	2054	2361
4	3	1769	1769	1117	1117	1769	1244	1521
5	4	1103	1103	354	354	1103	519	733
6	5	4936	340	2719	19	340	75	3146
7	5	4184	337	1607	337	337	202	2991
1	6	2682	2682	853	853	2682	1216	1685
2	7	5428	1571	3544	734	1571	864	4017
8	7	4933	1563	2529	59	1563	226	3503
13	8	2492	2492	852	852	2492	1180	1654
8	9	4933	340	2529	13	340	49	2958
14	9	4184	337	1607	337	337	202	1584
9	10	1174	1174	355	355	1174	536	867
10	11	2589	2589	1195	1195	2589	1445	1703
11	12	3655	3655	2615	2615	3655	2786	3052
7	13	4184	816	1607	816	816	488	3169
12	13	5431	828	3681	421	828	485	4114
6	14	4936	1565	2719	87	1565	345	3592
12	14	5431	1573	3681	799	1573	921	4142

TABLE IV
GA PARAMETERS

GA parameters	value
Number of generation	4000
Size of population	100
Initial population	random
Mutation	1.0

TABLE V
PARAMETER VARIATIONS

Case no.	α	β_1	$\beta_2,\beta_3,$ β_4,β_5	β_6
Case 1	0	100	2	2
Case 2	1	100	0	2
Case 3	1	100	2	2

TABLE VI
GA OUTPUTS (TSMS AND RELAY CHARACTERISTICS)

Relay Number	TSM				No of Selected Characteristic		
	Case1	Case2	Case3	Case4	Case1	Case2	Case3
1	1.641	0.050	1.121	0.273	1	5	1
2	0.851	0.050	0.050	0.343	6	5	5
3	1.629	0.517	0.516	0.287	1	4	4
4	0.872	0.097	0.096	0.155	1	4	4
5	0.723	0.050	0.050	0.129	1	4	4
6	0.998	0.077	0.659	0.384	6	5	6
7	1.518	0.784	0.784	0.269	1	1	1
8	1.037	0.084	1.653	0.414	6	5	1
9	0.785	0.050	0.050	0.132	1	4	3
10	1.420	0.492	0.161	0.237	1	8	3
11	2.000	0.330	0.050	0.303	1	3	5
12	2.000	0.786	1.516	0.461	3	3	1
13	1.390	0.050	0.150	0.247	1	5	2
14	0.050	0.819	0.186	0.243	5	1	4
Average Value	1.208	0.303	0.510	0.277	-	-	-

times of the first, second, and third zones of all distance relays have been 20(ms), 0.3(s), and 0.6(s) and all points of starting second zones of all lines are 80% of the lines. It is assumed that all of the lines are protected by distance and O/C relays, and the characteristics of O/C relays are formulated by (7) and the best of them will be chosen by GA to have the optimal coordination.

The network information is given in Appendix B. To obtain the OF, short-circuit (SC) currents of the main and backup O/C relays must be calculated on critical fault locations. The information of pickup current settings for the relays is given in Table II. As can be seen from Table II, the value of pickup current of each O/C relay is assumed to be approximately 1.2 times the relevant maximum load. This is because the important influencing factor is the maximum load current and many papers, such as [2] and [7], used the same manner. Also, the information, including some SC currents of the backup O/C relays for critical fault locations, is given in Table III.

The control parameters of GA are listed in Table IV. The process of finding the parameters of the OF is trial and error. The parameters of the expression have been found for two different networks (of this section and sample2) with a different configuration using the mentioned method. As a result, the same parameters are approved for them. However, for other networks,

TABLE VII
GA OUTPUTS (OPERATING AND DISCRIMINATION TIMES FOR THE CRITICAL FAULT POINT)

Main Dist Relay	Backup O/C Relay	Case1				Case2				Case3				Case4			
		Δt_{mbOC}		$\Delta t_{mbOCDIS}$		Δt_{mbOC}		$\Delta t_{mbOCDIS}$		Δt_{mbOC}		$\Delta t_{mbOCDIS}$		Δt_{mbOC}		$\Delta t_{mbOCDIS}$	
		F1	F2	F3	F4	F1	F2	F3	F4	F1	F2	F3	F4	F1	F2	F3	F4
2	1	0.59	0.35	0.60	0.08	0.59	0.35	0.08	0.60	0.50	0.65	0.51	0.49	0.78	0.66	0.35	0.79
14	1	0.59	0.00	0.60	0.03	0.59	0.00	0.03	0.60	0.51	0.29	0.52	0.08	0.79	0.00	0.07	0.80
3	2	0.00	0.05	0.61	0.06	0.00	0.05	0.06	0.61	0.09	0.26	0.16	0.11	0.00	0.08	0.08	0.61
4	3	0.11	0.16	0.59	0.00	0.11	0.16	0.00	0.59	0.00	0.30	0.10	0.06	0.11	0.16	0.00	0.59
5	4	0.00	0.75	0.42	0.71	0.00	0.75	0.71	0.42	0.00	2.70	0.06	0.93	0.00	0.75	0.72	0.42
1	6	0.77	-	0.78	0.00	0.77	-	0.00	0.78	0.57	-	0.58	0.00	0.78	-	-0.01	0.79
2	7	0.78	0.00	0.79	1.93	0.78	0.00	1.93	0.79	0.59	0.19	0.60	3.06	0.79	-0.01	1.94	0.80
8	7	0.08	0.21	0.56	0.00	0.08	0.21	0.00	0.56	0.00	0.09	0.43	0.20	0.07	0.27	0.00	0.68
13	8	0.59	0.22	0.60	0.00	0.59	0.22	0.00	0.60	0.20	0.07	0.21	0.00	0.60	0.22	0.00	0.61
9	10	0.59	-	0.60	4.32	0.59	-	4.32	0.60	0.20	-	0.21	2.12	0.60	-	4.58	0.61
10	11	0.06	0.44	0.90	0.44	0.06	0.44	0.44	0.90	0.11	0.30	0.47	0.00	0.17	0.38	0.00	0.77
11	12	0.58	-	0.59	0.00	0.58	-	0.00	0.59	0.23	-	0.24	0.00	0.78	-	0.00	0.79
7	13	0.60	0.00	0.61	2.03	0.60	0.00	2.03	0.61	0.24	0.02	0.25	0.44	0.79	0.00	0.97	0.80
12	13	0.05	0.93	0.19	0.00	0.05	0.93	0.00	0.19	0.00	0.76	0.09	0.11	0.14	0.59	0.00	0.56
6	14	0.10	0.07	0.26	0.00	0.10	0.07	0.00	0.26	0.08	0.46	0.20	0.24	0.00	0.09	0.06	0.55
12	14	0.11	0.14	0.51	0.12	0.11	0.14	0.12	0.51	0.06	0.01	0.34	0.00	0.09	0.12	0.00	0.75
7	13	1.22	0.44	1.23	1.66	1.22	0.44	1.66	1.23	0.40	0.00	0.41	0.47	0.79	0.00	1.04	0.80
12	13	1.20	1.46	1.21	1.25	1.20	1.46	1.25	1.21	0.39	0.27	0.40	0.15	0.78	0.51	0.35	0.79
6	14	0.40	-	0.41	1.40	0.40	-	1.40	0.41	0.04	-	0.05	2.60	0.60	-	1.98	0.61
12	14	0.40	0.01	0.41	0.00	0.40	0.01	0.00	0.41	0.03	0.26	0.04	0.00	0.60	0.06	-0.01	0.61
Average Value		0.44	0.38	0.62	0.70	0.44	0.33	0.70	0.62	0.21	0.28	0.29	0.55	0.46	0.33	0.61	0.69

especially for networks with a different configuration, the same approach (i.e., trial and error) should be applied to find the suitable parameters. For testing the effectiveness of GA for the purpose of O/C relays optimal coordination, two trials with different values of α, $\beta_1, \ldots, \beta_5$, and β_6 are tested. The variations of control parameter values are listed in Table V.

2) Results and Discussion: By applying the GA with selected values to the network of Fig. 7, the output results are obtained. TSMs and O/C relays characteristics selected by the GA are given in Table VI. The results are given for three different cases. Different parameter values for cases 1, 2, and 3 are listed in Table VI. The values of parameters for case 4 are the same as case 3, but in case 4, the fixed relay characteristic (characteristic number 2) has been considered for all relays. Therefore, we can have a comparison with the results of case 3.

In all cases, TSMs are considered to be continuous and in the range (i.e., 0.05 to 2). Discrimination times of relays for the fault at critical points of O/C-O/C and O/C-distance coordination are given in Table VII. The operating time of O/C relays (for the fault close to the CB) and the operating time of the second zone of distance relays are given in Table VIII. As mentioned in Section IV, all CTI values are considered to be 0.2 s. There are 20 M/B set relays for Fig. 7; therefore, for each critical fault location, 20 Δt exist.

In all cases, the discrimination time values greater than -0.01 and less than zero are considered zero. This means that in (11) and (12), when $-0.01 \leq \Delta t \leq 0$, the values compared to 0.2 s are very small and can be neglected. Therefore, $t_b - t_m \approx$0.2 s. The time interval of the main and backup relays for faults at the critical point is ideally 0.2 (i.e., Δt_{mb} of equations) to be zero. However, in practice, by using the described method of GA and choosing the suitable parameters, zero values of Δt_{mb} can be rarely obtained. But the small values of Δt_{mb} can be achieved. To check which case is suitable compared to the others (i.e., the suitable time intervals have been achieved), the Δt_{mb} for faults at the critical point are checked, and the negative values within $-0.01 \leq \Delta t_{\mathrm{mb}} \leq 0$ and small positive values are selected as a suitable case. A greater description relative to this selection will be given.

As can be seen from Table VII, in all assumed cases because of considering a great weight for satisfying the coordination constraints ($\beta_1 = 100$) almost all M/B discrimination times (Δt_{mb}) are positive values. There are only two small negative Δt_{mb} in case 4 without the characteristic selecting case.

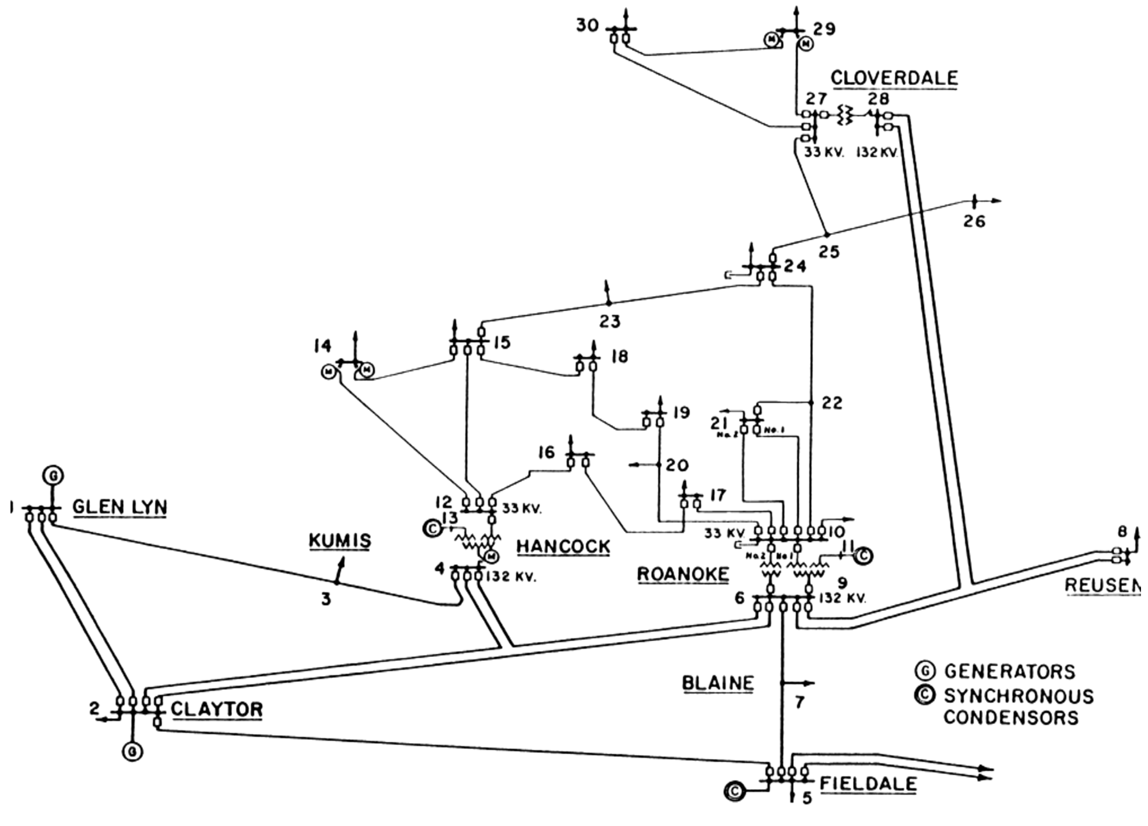

Fig. 8. IEEE 30-buses network.

In case 1, α is assumed to be zero. So the TSM and operating time of relays, which are shown in Tables VI and VIII, are without the weighting factor to control and have great values. On the other hand, the discrimination times for five critical conditions in Table VII have normal values when considering other suitable weighing factors.

To consider the role of the novelties of the OF (i.e., the two last terms of (7) and (8)), the results of GA without those terms are surveyed in case 2. It can be seen that in the old OF method, the TSMs and operating time $(\mathrm{t_{op}})$ of relays are small values. Despite the small values of TSMs and $\mathrm{t_{op}}$, the discrimination and operating times have large values for faults at the critical points as given in Table VII.

Therefore, the backup O/C relays will clear the faults late, while in the new OF method, the suitable relays characteristics are chosen, and this problem is solved.

In case 4, the coordination of O/C and distance relays is solved without selecting relays characteristics (i.e., the fixed characteristic (number 2) is used for all O/C relays). The relay characteristics are number 2, which is a standard inverse. As can be seen in Fig. 6, this characteristic is more inverse than characteristics 1 and 6. The results show that the TSM values of case 4 are smaller than case 3, but the operating times of relays with these settings that are given in Table VIII are much larger than case 3. The average O/C relays operating times is 0.65 s, which is 6 times greater than case 3. Also, the second zone operating time of the distance relays in case 4 is much greater than case 3. In Table VII, the average values of $\Delta t_{mbOC|F1|}$ and $\Delta t_{mbOCDIS|F3|}$ can be seen to be more in case 4 than in case 3.

TABLE VIII
GA Outputs (OPERATING TIME OF THE SECOND ZONE OF DISTANCE RELAYS AND OPERATING TIME OF O/C RELAYS FOR THE CLOSE IN FAULT)

Relay No	$\mathrm{t_{Z2}}$				t_{OP}			
	Case1	Case2	Case3	Case4	Case1	Case2	Case3	Case4
1	1.07	0.67	0.54	1.01	9.63	0.02	0.20	0.60
2	0.90	0.47	0.47	0.91	5.17	0.02	0.01	0.77
3	0.72	0.44	0.44	0.72	8.74	0.19	0.08	0.62
4	0.72	0.45	0.45	0.73	13.3	0.05	0.10	0.49
5	0.31	0.31	0.31	0.31	12.3	0.03	0.06	0.42
6	0.95	0.68	0.61	0.92	4.94	0.03	0.08	0.81
7	0.31	0.31	0.31	0.31	12.4	0.34	0.26	0.67
8	0.89	0.69	0.63	0.90	5.35	0.03	0.23	0.88
9	1.07	0.67	0.54	1.01	12.2	0.03	0.05	0.42
10	0.71	0.40	0.42	0.69	9.56	0.20	0.04	0.55
11	0.87	0.45	0.49	0.84	11.17	0.12	0.01	0.66
12	1.00	0.55	0.64	0.90	8.02	0.27	0.13	0.91
13	1.13	0.67	0.62	1.12	10.6	0.02	0.04	0.60
14	1.13	0.66	0.62	1.12	0.51	0.38	0.09	0.65
Aver.	0.84	0.53	0.51	0.82	8.87	0.12	0.10	0.65

Therefore, case 3 is consequently selected as a suitable case. In this case, miscoordination does not exist, and the backup O/C relays operating times have relatively small values. Also, the

TABLE IX
GA OUTPUTS (TSMs AND RELAY CHARACTERISTICS)

Δt	Case1		Case2		Case3		Case4	
	Number	Average	Number	Average	Number	Average	Number	Average
$\Delta t_{mb\|F_1\|} > 0$	224	0.995	221	1.291	226	0.756	214	1.421
$\Delta t_{mb\|F_1\|} < 0$	4	-0.08	6	-0.071	2	-0.051	14	-0. 077
$\Delta t_{mb\|F_2\|} > 0$	225	0.780	224	0.967	224	0.562	209	1.102
$\Delta t_{mb\|F_2\|} < 0$	3	-0.034	4	-0.066	4	-0.049	19	-0.097
$\Delta t_{mb\|F_3\|} > 0$	228	0.843	228	1.124	228	0.632	227	1.133
$\Delta t_{mb\|F_3\|} < 0$	0	0	0	0	0	0	1	-0. 029
$\Delta t_{mb\|F_4\|} > 0$	226	0.664	219	1.375	223	0.768	214	0.657
$\Delta t_{mb\|F_4\|} < 0$	2	-0.021	9	-0.091	5	-0.0631	14	-0.105
t_{Z2}	Average =1.26		Average =0.66		Average =0.68		Average =1.03	
t_{OP}	Average =1.06		Average =0.72		Average =0.42		Average =0.96	

TABLE X
GA OUTPUTS (TSMs AND RELAY CHARACTERISTICS)

	Case1	Case2	Case3
No. of Selected Char.	Relay No.	Relay No.	Relay No.
1	3,4,5,9,,11,13,19,28,29,30,37,42 ,44,46,48,49,50,51,52,53,58,59 ,61,64,65,66,68,70,71,73,80,85	2,3,6,7,10,12,14,15,16,17 ,18,20,21,24,25,28,29,30,31 ,34,36,38,39,40,41,42,43 ,45,46,49,52,53,64,66,67,68,69,70,72,73,74,76 ,78,82,83,85	2,4,5,7,14,15,17,19 ,25,29,31,32,36,39,42,43 ,44,46,47,48,49,50,52,54,55 ,56,58,59,63,71,76,77,83,85,86
2	6,8, 15,16,20, 22,24,27,32,33, 35 ,36,38,39,40, 47,554,55 .57, 60, 67,75,76, 79, 81,83	1,4,5,8,9, 13,19,22,26 ,27,32,37,44,47,48,51,55,60 ,61,71,75,77,80,81,86	8,9,16,33,40,62,73,75,78,84
3	2,7,10,17,26,62,74,78	23,33,35,65,79	1,3,21,30,34,64,66,80,81,82
4	12,14,18,21,25,31,34, 43,45,56, 63,69,77,82,84,86,	58	10,11,12,13,18,20,22,23,26,38 ,41,45,51,53,57,67,69,70,72,79
6	41,54,72	-	6,27,60,68,74
7	23	11,84	24,28,
8	-	-	35,37,61,65

operating times of O/C and distance relays are smaller than the results of previous methods. Therefore, it is revealed that the new OF plus considering O/C relay characteristics is effective.

B. Sample 2

The second network is the IEEE 30-buses system which can be considered as a meshed subtransmission/distribution system. Again, the description of this network application is given in two subsections. The first subsection includes network information and protection data and the second one includes the obtained results and the related discussion.

1) Network and Protection Data: The network consists of 30 buses (132- and 33-kV buses), 37 lines, 6 generators, 4 transformers, as well as 86 O/C relays and 86 distance relays. Fig. 8 shows the system. The same 8 characteristics mentioned in Table I are assumed for O/C relays. The generator, transmission lines, and transformer information are given in [14].

2) Results and Discussion: Again, the GA with selected values of α, $\beta_1, \ldots, \beta_5$, and β_6 are given in Table V and GA parameters given in Table IV have been applied to the network of Fig. 8. The summary of the discrimination and operating times is given in Table IX. The detailed relative information of all relays is not given here because of space limitations. The O/C relays characteristics selected by GA are also listed in Table X.

The rows of Table IX consist of $\Delta t_{\mathrm{mb}|F_1|}$, $\Delta t_{\mathrm{mb}|F_2|}$, $\Delta t_{\mathrm{mb}|F_3|}$, and $\Delta t_{\mathrm{mb}|F_4|}$ greater than zero (fully coordination), $\Delta t_{\mathrm{mb}|F_1|}$, $\Delta t_{\mathrm{mb}|F_2|}$, $\Delta t_{\mathrm{mb}|F_3|}$, and $\Delta t_{\mathrm{mb}|F_4|}$ smaller than zero (miscoordination) and the average of operating times of O/C and zones of distance relays. The information values for each case are the number of M/B relays and average of them, respectively. The last two rows of Table IX relate to averages O/C relays operating times for close-in fault and the second zone operating time of distance relays.

The comparison of four cases described in the previous example is performed on a greater network. In this network, as in the previous sample, simulation results show that case 3 uses a new OF with selecting O/C relays characteristics that have presented better outputs in comparison to other cases that are based on old methods.

Although the average of operating times in case 2 is suitable and smaller than the average of operating times of cases 1 and 4, in case 1, despite having low discrimination times for faults in the critical points, the average operating times for O/C relays and the second zone of distance relays are so large and the results of coordination are not useful.

In case 4, the fixed characteristics of O/C relays are used in the coordination algorithm, the discrimination times have large positive values. Also, the operating times of distance (t_{Z2}) and O/C (t_{OP}) relays result in greater values in comparison to case 3. It can be seen from Table IX, that the misscoordination number for case 4 is 48. In other words, this method cannot give a good coordination for large networks.

As can be seen from Table X, most of the characteristics selected for the O/C relays are number 1 (short time inverse) and number 2 (standard inverse). The reason is that the values of $\beta_1, \ldots, \beta_6$ in these cases make the coordination constraints more important than the others.

Similar to example 1, for this network also, it has been shown that case 3 is the suitable one. The comparison between cases 3 and other cases revealed that although in some parameters the cases are similar to each other, to obtain optimal coordination of O/C and distance relays, the method of case 3 is more efficient.

VI. CONCLUSION

A new optimal method for distance and O/C relay coordination based on GA has been developed. In the proposed method, the OF of optimal O/C relays coordination has been fully modified by adding some new terms which fulfill the optimal combined coordination of distance and O/C relays. Various relay characteristics have been considered for each O/C relay, and the best of them have been selected by GA to make optimal coordination easier. The computer program has been tested on two different power system networks (i.e., IEEE 30 buses and 8 buses system). From the obtained results, it has been shown that the new method is successful and efficient.

APPENDIX A

The flow diagram of the GA application to O/C relay coordination is given in Fig. 9.

APPENDIX B

The information of the sample network in Fig. 7 is given in Tables XIV–XVI [6], [9], [11], and [12]. They are based on 100 MVA and 150 kV.

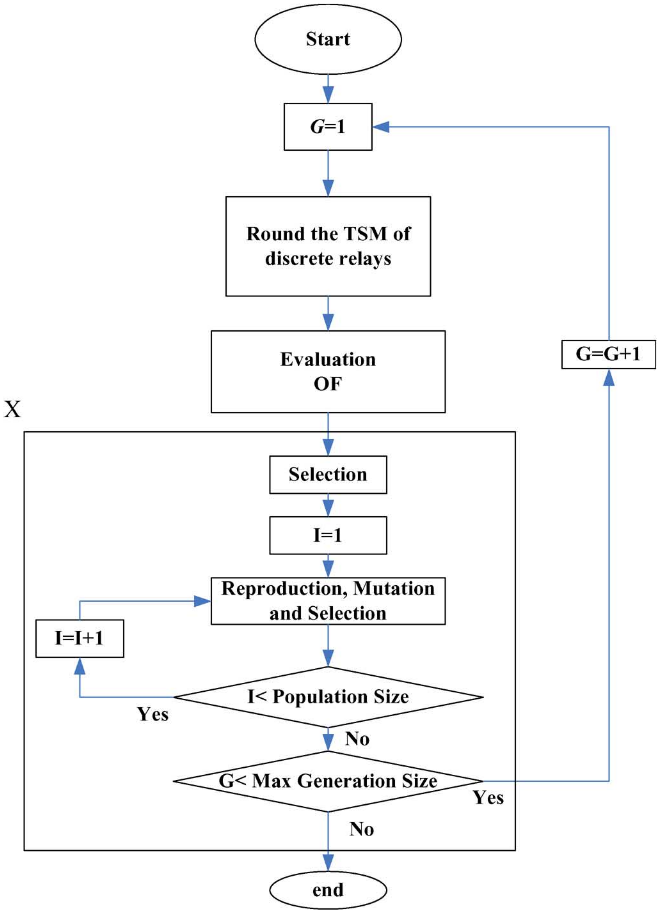

Fig. 9. Flow diagram of GA application to overcurrent relay coordination.

TABLE XI
LINES' INFORMATION

Line	R (pu)	X (pu)	V (kV)
1	0.0018	0.0222	150
2	0.0018	0.0222	150
3	0.0018	0.02	150
4	0.0022	0.02	150
5	0.0022	0.02	150
6	0.0018	0.02	150
7	0.0022	0.0222	150

TABLE XII
GENERATORS' INFORMATION

Generators	X (pu)	V (kV)
	0.1	10

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