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Optimal coordination of directional overcurrent relays in distribution systems based on network splitting

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SUMMARY

In real case of distribution systems with several directional overcurrent relays, the designer is facing an optimization problem with an extensive search space of discrete values. Finding the optimal solution to such a problem is a time-consuming task with big chance of nonconvexity. In this paper, the optimal coordination of directional overcurrent relays in distribution systems is modeled by attempting the practical issues, that is, full discrete variables for time-current curve, time multiplier setting, and plug setting. To reduce the calculation time, the problem is solved by using a novel method based on network splitting. The problem is solved in two stages: the first one finds the optimal solution for the subnetworks individually and the second one determines the optimal setting for the relays on the tie lines connecting the subnetworks. It is shown that the proposed method improves the relays' operating times and also reduces the chance of nonconvexity of the problem. By applying the proposed method to the 30-bus Institute of Electrical and Electronics Engineers test system, the results are compared with the conventional algorithms. It is found how the practical issues related to the relay characteristics selection can affect the overall relays' time. Also, the computation time is considerably reduced with network splitting method presented in this paper. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: directional overcurrent relay; optimal coordination; genetic algorithm; integer nonlinear programming

1. INTRODUCTION

Directional overcurrent relays (DOCRs) are still the best choice for protection of distribution systems. Coordination of DOCRs in interconnected systems is complicated and difficult to solve by conventional coordination methods. Generally, the coordination of DOCRs requires the selection of plug setting (PS) and time multiplier setting (TMS). These parameters should be specified such that all equality and inequality constraints are satisfied under the shortest operation time of the relays. Several methods such as linear programming [1–3], nonlinear programing [4,5], artificial intelligence techniques [6–8], and hybrid algorithms [9–13] are used to solve this optimization problem.

In linear programming method, the PSs are selected regarding to maximum load currents, and only the value of TMS is optimized. Despite the simplicity, this will not lead to an optimal solution. Nonlinear programming methods can find the optimal value of both PS and TMS, but they are complex, time-consuming, and hardly converged [14]. It should be noted that PS and TMS of the relays have discrete values, so the results obtained by using continuous variables should be rounded off to the nearest available discrete values. The rounding of the program output values may lead to inaccuracy in values of the relay settings. In [13], the problem has been solved by mix integer programming and TMS values assumed to be continuous. The modern DOCRs have several characteristics to select in order to improve the speed of protection system. In many publications [1–9], the International Electrotechnical Commission (IEC) normally inverse (NI) characteristic is used for all relays. In [15],

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each optimization parameter is optimized independently with the aid of linear formulation of the coordination problem, and the coordination is performed in three steps to determine PS, TMS, and TCC of the relays. This method improves the relays operation times compared with the single characteristic methods, but it does not lead to an optimal solution either.

In this article, the relays' operational characteristics are considered as optimization variables along with TMS and PS of the relays. The optimization problem is solved by genetic algorithm (GA). New operators are defined for the GA to produce discrete populations for three sets of variables, that is, PS, TMS, and TCC of the relays. The most important contribution of this paper is the proposed method for reducing the calculation time and improving the chance of feasibility and relays' operating times. On the basis of the proposed method, the under study network is split into smaller subnetworks. For each of the subnetworks, the optimization modeling is performed, and the individual solution for each model is determined; it coordinates the relays on each subnetwork independently, and the procedure is continued by defining a linkage optimization model that reestablishes the links between subnetworks. The linkage optimization problem is a relatively small problem in which only the relays on the tie lines between subnetworks and their adjacent relays are involved. This method reduces the relays' operating times and overcomes the long run time of the optimization program and also reduces the chance of nonconvexity.

2. PROBLEM FORMULATION

A fault simulated near the relay i on the line is named near-end fault for the relay under consideration, and similarly, the furthest fault to the relay on the end of the line is a far-end fault for the relay. In Figure 1, the near-end fault and far-end fault for relay i are shown. The near-end fault level is used to coordinate relay operations for high fault currents very close to relay (i.e., at the beginning of line). The far-end fault level coordinates the relays for the minimum fault current at the end of the line. In many researches, the near-end fault method is used to coordinate the DOCRs. This will increase the relays' operating times for far-end faults, and by using different characteristics, this problem will become more acute, so the objective function is defined as the summation of the primary operating times of relays for both near-end and far-end faults as shown in the succeeding texts [16,17]:

$$\min Z = \sum_{i=1}^{n} \alpha_i \left(t_i^N + t_i^F\right) \tag{1}$$

where

t_i^N relay i operation time for near-end fault
t_i^F relay i operation time for far-end fault
α_i weight factor for relay i (considered to be 1 for all relays)
min Z objective function

The fault current is sensed by both primary and backup relays, but the backup relays should only operate when the primary relays fail to send the signal to the circuit breaker. The minimum operating time of backup relays are determined by the primary relays and circuit breaker operating times and overshoot time. This constraint should be regarded for all primary and backup relays and in all fault currents. Figure 2 illustrates the problem caused by near-end fault approach. It shows that consideration of only near-end faults in selectivity constraints may lead to inconsistency between primary and backup relay in lower fault currents, so like the objective function, the constraints also are considered on the basis of both near-end and far-end faults as shown in the succeeding texts [4]:

Figure 1. Near-end and far-end faults for relay i.

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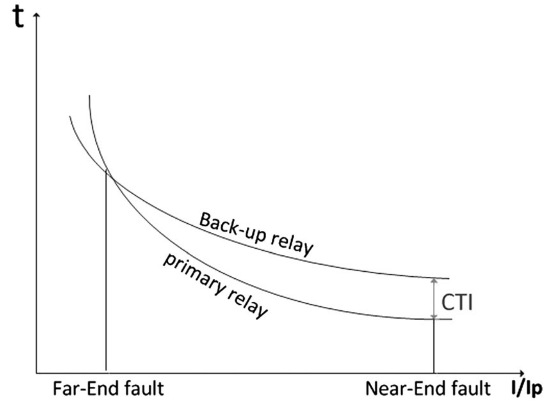

Figure 2. Primary and backup relays' time curves.

$$t_j^N - t_i^N > \mathrm{CTI} \tag{2}$$

$$t_j^F - t_i^F > \mathrm{CTI} \tag{3}$$

where

t_j^N backup relay j operation time for near-end fault
t_i^N primary relay i operation time for near-end fault
t_j^F backup relay j operation time for far-end fault
t_i^F primary relay i operation time for far-end fault
CTI coordination time interval

The coordination time interval is assumed to be 0.2 s for all relays. The TMS of each relay directly affects the operating time of the relay. The bounds on TMS of relays can be stated as follows:

$$\mathrm{TMS}_{\mathrm{i,\,min}} < \mathrm{TMS}_{\mathrm{i}} < \mathrm{TMS}_{\mathrm{i,\,max}} \tag{4}$$

where

$\mathrm{TMS}_{\mathrm{i,min}}$ minimum allowed TMS for relay R_i
$\mathrm{TMS}_{\mathrm{i,max}}$ maximum allowed TMS for relay R_i
$\mathrm{TMS}_{\mathrm{i}}$ TMS of relay R_i

The bounds on pickup setting of the relays can be stated as follows:

$$\mathrm{Ip}_{\mathrm{i,\,min}} < \mathrm{Ip}_{\mathrm{i}} < \mathrm{Ip}_{\mathrm{i,\,max}} \tag{5}$$

where

$\mathrm{Ip}_{\mathrm{i,min}}$ minimum value of relay R_i pickup
$\mathrm{Ip}_{\mathrm{i,max}}$ maximum value of relay R_i pickup
Ip_{i} relay R_i pickup current

The minimum limit of TMS indicates how fast the relay can operate in order to let the transient condition pass and prevents wrong trips, and the maximum limit indicates the maximum allowable fault clearing time. The TMS bounds are, respectively, considered to be 0.1 and 1.3.

The minimum PS of the relay is the maximum value between the minimum available tap setting and a four-third of the maximum load current passes through it. The maximum PS considered to be two-third of the minimum fault current seen by the relay as backup [10,18]. These considerations assure that the relay does not trip in overload condition and also senses the far-end faults of the lines under protection as backup relay. The upper bounds are rounded off to the lower available tap settings, and the lower bounds are rounded off to the upper available tap settings. The aforementioned rules

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for PS bounds are applied to the Institute of Electrical and Electronics Engineers (IEEE) 30-bus test system, and the results are shown in Table I. These values are considered in the optimization model as the constraints on relay tap settings.

As explained in the first section, generally, PS and TMS of relays are considered as optimization variables. In this article, the relays' characteristics are considered as optimization variables as well. Three main and common standard characteristics are considered for the relays in our modeling, that is, IEC NI, very inverse, and extremely inverse. The formulation and the parameters of these curves are given in IEC standards as illustrated in Table II.

3. INTEGER PROGRAMMING BASED ON GENETIC ALGORITHM

Like all other algorithms, GA starts with objective function specification and defining optimization variables and ends with convergence test. In the first step, the initial population is produced; then, by applying the mutation and crossover operators, the next population is generated. Normally, the members of new generated population will have continuous values like the previous generation. To adapt the algorithm to produce discrete values, new mutation and crossover operators should be defined. These new operators make the GA program to be applicable to nonlinear integer programming, which is our requirement in relay coordination problem. The hybrid GA-NLP method produces continuous values for TMS and pickup current of the relays, and the GA-LP method can produce discrete values only for pickup currents of the relays, so they cannot be used in this case.

The most important problem that GA has is the nonconvexity in large-scale and highly constrained problems. It also is very time-consuming in these cases. To overcome these problems, a new method based on network splitting (NS) is presented in the next section.

Table I. PS bounds in amperes.

Relay no.	$I_{p,min}$	$I_{p,max}$	R. No	$I_{p,min}$	$I_{p,max}$	R.No	$I_{p,min}$	$I_{p,max}$
1	420	1150	14	150	1130	27	350	400
2	270	2450	15	220	750	28	60	580
3	490	2130	16	120	560	29	60	1280
4	440	1030	17	110	1200	30	190	930
5	460	880	18	130	570	31	70	700
6	460	1400	19	210	920	32	70	520
7	360	1910	20	370	1920	33	120	480
8	360	1800	21	270	420	34	130	550
9	580	740	22	340	390	35	130	1010
10	140	1760	23	90	750	36	190	530
11	140	220	24	210	250	37	170	630
12	330	430	25	420	590	38	200	430
13	140	1230	26	190	1270	39	190	230

Table II. International Electrotechnical Commission (IEC) standard characteristics for inverse time relays.

IEC standard characteristics	$t = \frac{A \times TMS}{\left(\frac{If}{Ip}\right)^B}$	
	A	B
IEC normally inverse	0.14	0.02
IEC very inverse	13.5	1
IEC extremely inverse	80	2

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4. NETWORK SPLITTING METHOD

Recently, several methods are provided to improve the optimization speed in coordinating the DOCRs. Among them, the hybrid methods have had the greatest success. They are usually based on GA, and another algorithm is used to evaluate some of the optimization variables and decreasing the search area of the GA [16]. Some other methods use GA to determine initial value and nonlinear programming to find global optimum values [8]. Despite reducing the optimization time, in large interconnected systems, finding a feasible solution will not be easy in these methods. Also, generating discrete values for both PS and TMS is not possible in these methods. Large networks usually include of several rings, and this specification makes the optimization problem difficult to solve because of high interrelations between constraints. Each ring adds several constraints to the optimization problem, and more constraints decrease the optimization speed and the chance to achieve a feasible solution. The proposed method divides the network into several parts to decrease the dimensions of the optimization problem then link them by a complementary algorithm. As a consequence of the dimension reduction, the optimization speed and the chance to find a feasible solution will be increased significantly. The number of divisions depends on the network size, utilized solver engine, and available hardware facilities to execute the optimization program. Usually, two divisions will be sufficient for normal size distribution networks (<40 bus), and for very large systems, more divisions will be effective. It should be noted that for each NS, some coordination constraints will be lost. To resolve the eventual miscoordinations, an analytical method is presented to satisfy all the related constraints. This should be performed once for each time that the optimization problem for every segregated part of the network is solved. Another important point is how split the network to cause the most simplification, optimization time reduction, and prevent infeasibility. In this regard, many approaches have been treated, and it has been determined that the network reduction will lead to the expected results if the following points are considered in the NS. These points are stated in order of priority:

(1) The number of created subnetworks should be low as much as possible:

More subnetworks mean more subproblem to be solved and less chance to find a feasible solution. So the number of subnetwork should be low. Two or three subnetworks would be enough for normal size distribution systems, and more divisions would be appropriate for very large networks.

(2) The NS results in minimum eliminated lines:

Each line has two main relays and several backup relays. It means that for every eliminated line, several constraints will be disregarded, and they should be considered in complementary optimization that it will decrease the chance of feasibility.

(3) The number of rings should be reduced:

In addition to the calculation time, the probability of finding a feasible solution in GA has a direct relation to the number and complexity of constraints. In an interconnected system, each loop makes a set of related constraint to the optimization problem and reduces the chance of convergence. If the loop is eliminated, the calculation speed and probability of finding a feasible solution will be increased. It should be noted that it is a prerequisite for any split to eliminate at least one ring.

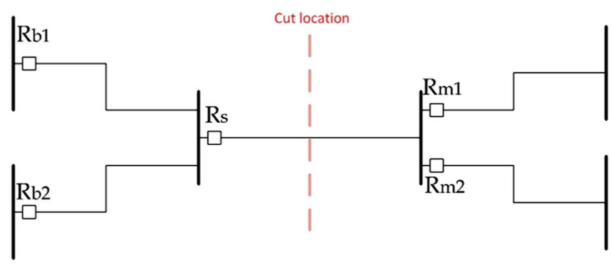

Figure 3. A disregarded relay and the adjacent main and backup relays.

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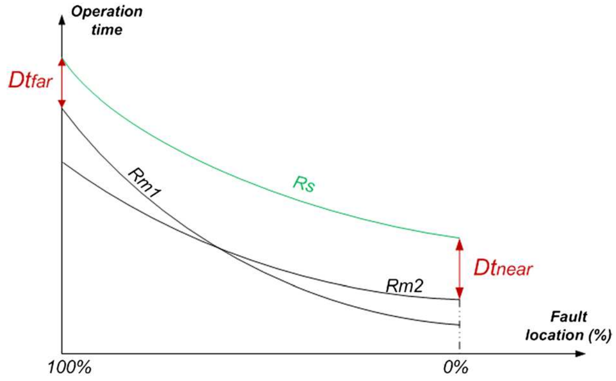

Figure 4. Time curves of the disregarded relay and the adjacent main relays.

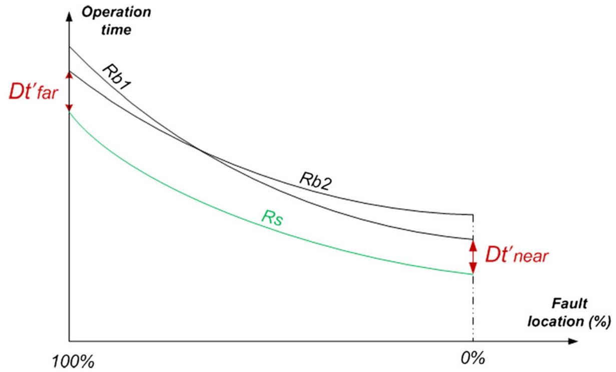

Figure 5. Time curves of the disregarded relay and the adjacent backup relays.

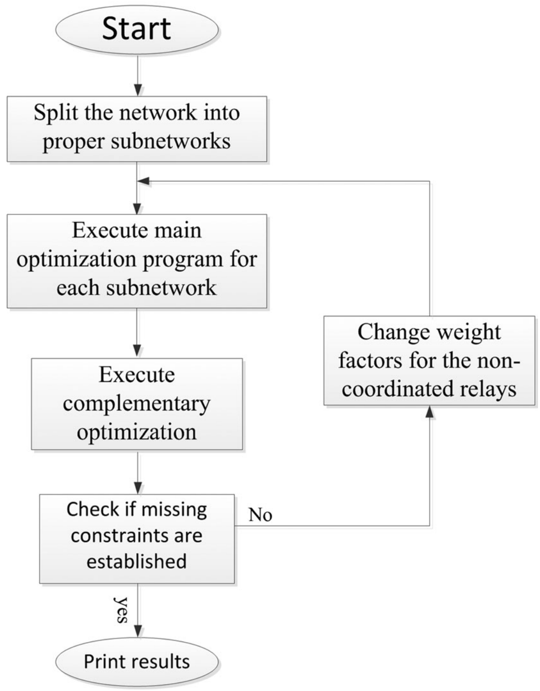

Figure 6. Proposed method based on network splitting.

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(4) The subnetworks should not have very different sizes:

Consider a system having n relays, N available pickup current tap setting points, M available TMS points, and R available characteristics for each relay. In this system, the search space of GA will have $(N \times M \times R)^n$ states. By splitting the network into two parts, the total search space of GA will have $(N \times M \times R)^{n1} + (N \times M \times R)^{n2}$ states where $n_1 + n_2 = n$. It can be shown that the search space has its minimum value if $n_1 = n_2 \pm k$ where $k = 1$ or 0 when n is odd or even, respectively. The calculation time of the optimization program will be decreased significantly if the search space of GA is reduced, and it will be reduced the most if the divisions be the same size.

The subnetworks should be created by regarding these four important points; otherwise, it would be an improper subnetwork resulting in the chance of infeasibility, and the calculation time will not be decreased as expected. After splitting the network into proper subnetworks, the created subnetworks should be treated as isolated networks, and the relays on each of them should be coordinated separately. This will be the first stage of the NS method and is named as main optimization. In this stage, each subnetwork has an objective function and a set of constraints according to Equations (1)–(3). After the relays on each subnetwork are coordinated separately, the ignored constraints related to the relays of the omitted lines should be satisfied. For this purpose, a secondary optimization problem should be presented. This stage is named as complementary optimization. To achieve the optimal operation time for the disregarded relays, a new fitness function is defined in the succeeding texts for this complementary optimization:

$$\min Z = \sum_{i=1}^{k} \left(\Delta t_{far^i} + \Delta t_{near^i} \right) \tag{6}$$

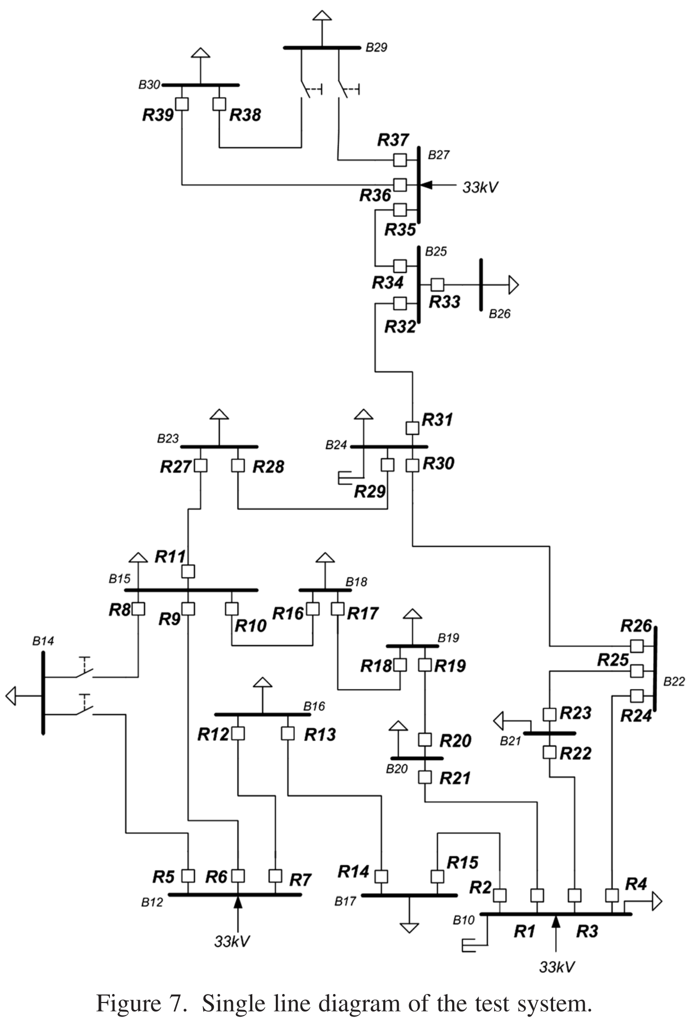

Figure 7. Single line diagram of the test system.

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$$\Delta t_{far^i} = t^s_{far^i} - \max\left(t^{m1}_{far^i}, t^{m2}_{far^i}, \dots\right) \quad (7)$$

$$\Delta t_{near^i} = t^s_{near^i} - \max\left(t^{m1}_{near^i}, t^{m2}_{near^i}, \dots\right) \quad (8)$$

where

$t^s_{far^i}$ i_{th} disregarded main relay operation time due to far-end faults

$t^s_{near^i}$ i_{th} disregarded main relay operation time due to near-end faults

$t^{m1}_{far^i}$ operation time of first backup relay of i_{th} disregarded main relay due to far-end faults

Table III. Relay setting results for approach 1.

Relay no.	PS	TMS	Relay no.	PS	TMS
1	420	0.41	21	270	0.23
2	270	0.5	22	340	0.16
3	500	0.35	23	170	0.4
4	440	0.24	24	210	0.27
5	460	0.1	25	420	0.22
6	460	0.38	26	660	0.21
7	1650	0.17	27	350	0.22
8	360	0.1	28	100	0.37
9	580	0.12	29	700	0.18
10	430	0.36	30	430	0.18
11	140	0.45	31	70	0.39
12	330	0.24	32	70	0.38
13	440	0.32	33	120	0.1
14	150	0.44	34	130	0.22
15	220	0.36	35	220	0.34
16	150	0.32	36	190	0.17
17	670	0.22	37	170	0.17
18	430	0.27	38	200	0.1
19	210	0.33	39	190	0.1
20	370	0.36			

PS, plug setting; TMS, time multiplier setting.

Table IV. Relay setting results for approach 2.

Relay no.	PS	TMS	Characteristic	Relay no.	PS	TMS	Characteristic
1	750	0.27	E	21	270	0.1	E
2	1220	0.1	V	22	340	0.1	V
3	1550	0.14	E	23	650	0.62	E
4	630	0.47	E	24	210	0.37	N
5	660	0.6	E	25	510	0.27	E
6	780	0.43	E	26	570	0.24	E
7	810	0.31	E	27	350	0.19	E
8	390	0.57	E	28	400	0.16	E
9	620	0.2	V	29	220	0.81	E
10	150	0.3	N	30	280	0.57	E
11	170	0.61	V	31	540	0.15	E
12	330	0.16	E	32	400	0.11	V
13	570	0.17	E	33	230	0.54	E
14	560	0.15	E	34	310	0.13	E
15	250	0.56	E	35	560	0.13	V
16	200	0.56	E	36	190	0.22	V
17	470	0.19	E	37	310	0.39	E
18	230	0.76	E	38	200	0.1	V
19	300	0.25	E	39	190	0.1	N
20	410	0.45	E				

PS, plug setting; TMS, time multiplier setting; N, normally inverse; V, very inverse; E, extremely inverse.

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$t^{m2}_{far^i}$ operation time of second backup relay of i_{th} disregarded main relay due to far-end faults
$t^{m1}_{near^i}$ operation time of first backup relay of i_{th} disregarded main relay due to near-end faults
$t^{m2}_{near^i}$ operation time of second backup relay of i_{th} disregarded main relay due to near-end faults

The constraints of the complementary optimization problem are considered as follows:

$$\Delta t_{far^i} > \mathrm{CTI} \tag{9}$$

$$\Delta t_{near^i} > \mathrm{CTI} \tag{10}$$

After running this optimization, two other constraints should be checked to be established. The constraints are defined as follows:

$$\Delta t'_{far^i} = \min\left(t^{b1}_{far^i}, t^{b2}_{far^i}, \ldots\right) \text{-} t^{s}_{far^i} > \mathrm{CTI} \tag{11}$$

$$\Delta t'_{far^i} = \min\left(t^{b1}_{near^i}, t^{b2}_{near^i}, \ldots\right) \text{-} t^{s}_{near^i} > \mathrm{CTI} \tag{12}$$

Every omitted line has two disregarded relays, and every disregarded relay has some backup relays, and the relay itself is a backup of some other main relays. Figure 3 shows an omitted line and the disregarded relays, and Figures 4 and 5 show the corresponding time curves of a disregarded relay and, respectively, the adjacent main and backup relays. Figure 4 represents the constraints 9 and 10, and Figure 5 represents the constraints 11 and 12.

If the constraints 11 and 12 are not satisfied, it means that the operation time of the backup relays of the disregarded relay should be increased. For this purpose, the weight factors of this relays should be

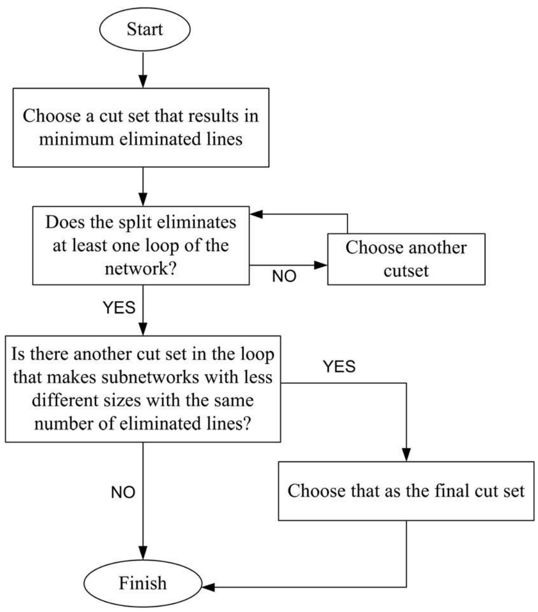

Figure 8. Flowchart of making proper subnetworks.

Table V. Procedure of making proper subnetworks from the test network.

Split number	Eliminated lines	Are any loop eliminated?	Number of relays in each subnetwork
1	R34-R35	No	5–34
2	R31-R32	No	8–31
3	R37-R38 and R36-R39	Yes	2–37
4	R13-R14 and R7-R12	Yes	2–37
5	R26-R30 and R28-R29	Yes	11–28
6	R26-R30 and R11-R27	Yes	13–26

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changed, and the main optimization should be executed again. Changing the weight factor will have a reverse influence on the relay operating time. It means that the weigh factors of the backup relays should be decreased. After running the main optimization, the complementary optimization should be executed, and the inequalities 11 and 12 should be checked again. This process will continue until all the constraints are satisfied. The flowchart of the proposed method based on the NS is shown in Figure 6.

5. TEST SYSTEM

The single line diagram of the 30-bus IEEE test system is shown in Figure 7. The system has three voltage levels (11, 33, and 132 kV), but only the relays on 33 kV lines are coordinated. Thirty-nine DOCRs are installed on these lines, and they are coordinated by three approaches to see how different characteristics and NS affect the coordination problem. GA with the new operators is used for optimization in all three approaches.

(1) Single characteristic:

All characteristics assumed to be IEC NI and the PSs and TMSs are determined by optimization. The resulted PS and TMS of the relays are shown in Table III.

(2) Different characteristics: conventional method:

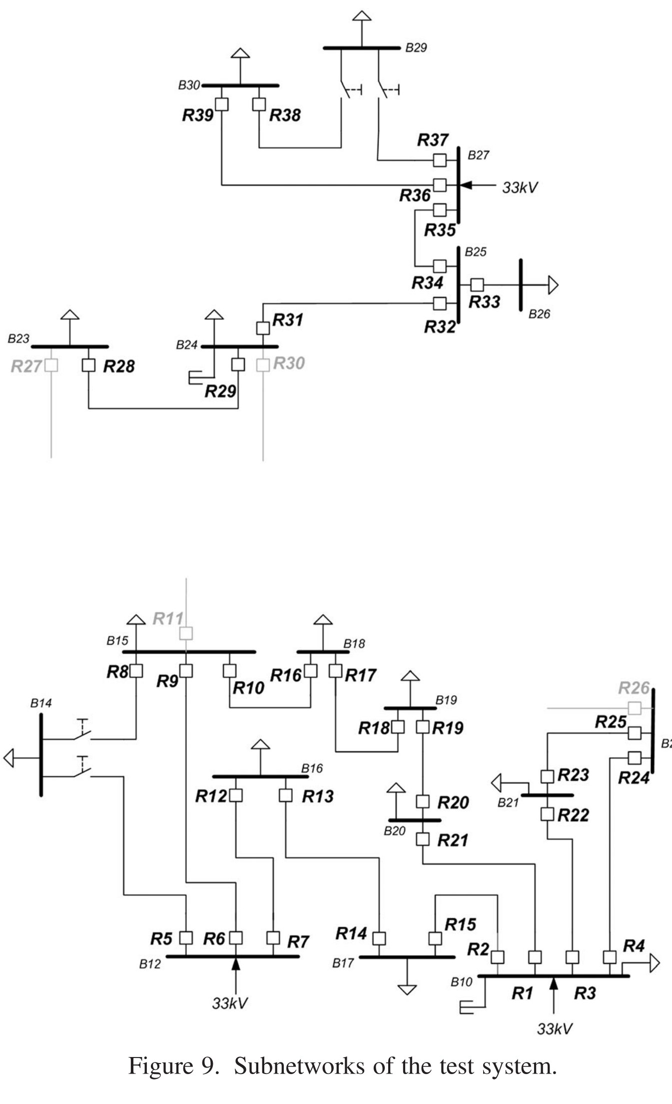

Figure 9. Subnetworks of the test system.

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In this case, the relays' characteristics are considered as optimization variables as well as the PS and TMS of each relay. The TMS, PS, and characteristic of all 39 relays are obtained by solving the optimization problem. The results are given in Table IV.

(3) Different characteristics: NS method:

The relays are coordinated using proposed NS method. The test network divided into two parts, and the relays on each part are coordinated similar to the approach 2. The flowchart and procedure of making proper subnetworks from the test network are, respectively, shown in Figure 8 and Table V. In the first step, the cut sets with the minimum eliminated lines are selected. There are two cut sets in this step, but none of them eliminate any loop of the network that makes them improper. In the next step, the cut sets with two eliminated lines are selected, and the one that leads to minimum difference in subnetwork sizes is selected as the final split. Figure 9 shows the resulted subnetworks.

After the subnetworks are created, the relays are coordinated using the proposed method. The GA parameters for main and complementary optimizations are given in Table VI.

Performance of the proposed method can be seen in Figure 10. This figure shows how the proposed method is converged in two main iterations. In the first main iteration, the coordination is performed for the relays inside of each subnetwork then the complementary optimization is performed to coordinate the disregarded relays on the tielines, but no feasible solution is found in the first main iteration. In this iteration, all of the weight factors are equal to 1. For beginning the second iteration, the weight factors of the tielines' backup relays in the subnetworks should be decreased. For each iteration, this factor is multiplied by 0.5, and for main iteration 2, the coordination is performed again with the new weight factors then the complementary optimization is performed, and a feasible solution is found, and it means that all of the relays are coordinated and the optimization ends in this point.

Table VI. Utilized GA parameters for the proposed method.

	Number of iterations			Fitness function final value	
	Main optimization	Subnetwork	Population size	Subnetwork 1	Subnetwork 2
Main optimization	2	100	50	20.34	7.12
Complementary optimization	2	10	20	2.88	

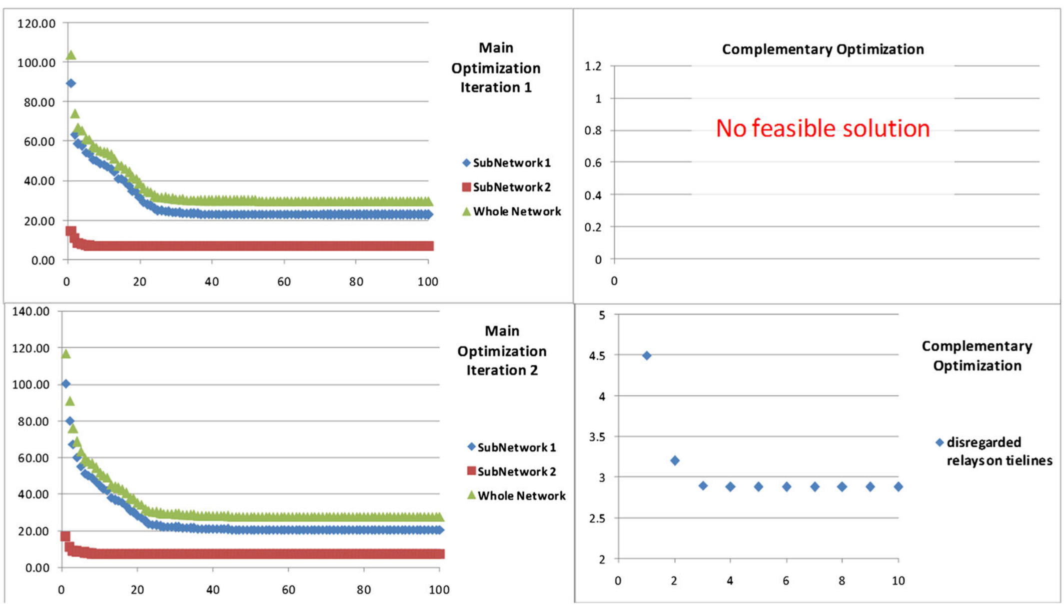

Figure 10. Iterations to reach the results in network splitting method.

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Table VII. Relay setting results for approach 3.

Relay no.	PS	TMS	Characteristic	Relay no.	PS	TMS	Characteristic
1	420	0.17	N	21	270	0.12	E
2	450	0.75	E	22	340	0.1	V
3	1810	0.1	E	23	650	0.63	E
4	830	0.14	E	24	210	0.28	V
5	580	0.37	E	25	590	0.15	V
6	1290	0.1	E	26	370	0.46	E
7	1030	0.1	V	27	350	0.16	V
8	470	0.2	E	28	320	0.2	V
9	580	0.13	N	29	230	0.82	E
10	360	1.06	E	30	190	0.36	V
11	220	0.55	V	31	240	0.59	E
12	340	0.1	E	32	180	0.38	E
13	520	0.17	E	33	290	0.2	E
14	280	0.59	E	34	280	0.22	E
15	330	0.25	E	35	280	0.33	E
16	370	0.13	E	36	250	0.31	E
17	420	0.57	E	37	240	0.29	E
18	230	0.67	E	38	200	0.1	E
19	210	0.79	V	39	190	0.1	N
20	920	0.1	V				

PS, plug setting; TMS, time multiplier setting; N, normally inverse; V, very inverse; E, extremely inverse.

Table VIII. Comparison of the 3 approaches.

Case no.	Single characteristic	Different characteristic conv.	Different characteristic network splitting
Summation of relays operating times for near-end and far-end faults (2 × 39)	59.29 s	35.71 s	31.58 s
Average operation time for each relay	0.76 s	0.457 s	0.404 s
Time required	2 h	3 h	7 min

System: cpu.core2due.E7500, ram 4 g. ddr3, windows7.x64

The TMS, PS, and TCC of every 39 relays corresponding to this approach are shown in Table VII.

The summation of relays' operating times for near-end and far-end faults, the respective average operation time of each relay, and the running time of the optimization program corresponding to each approach are given in Table VIII. By comparing approaches 1 and 2, this is clear that the relay operating times are improved significantly in approach 2. It shows that using several characteristics in coordinating DOCRs are very useful. Approaches 1 and 2 are very time-consuming, and the optimization will be feasible after several executions, but by using NS method, the optimization will be easily converged, and the calculation time for this method is much less than the conventional method. On the other hand, the value of the fitness function is a bit better in NS method.

6. CONCLUSION

A new method based on NS is presented for optimal coordination of DOCRs in power distribution systems. The method determines the optimal values for PS and TMS of the DOCRs, all as discrete variables, and also specifies optimally the relay characteristic. The modeling of the optimization problem then leads to a nonlinear integer programming that is solved by an adopted GA with integer variables. The proposed coordination problem modeling is applied to the 30-bus IEEE test system, and the problem is treated by three approaches to be able to compare the effectiveness of the proposed method. The results compare the approach with conventional GA and single relay characteristic for all DOCRs and the approach in which the relay' characteristics are considered as optimization variables. Furthermore, the latter approach is compared with the proposed method of NS. It is shown that using the relays'

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characteristics as optimization variables will lead to lower operation times for many relays that results in a reduction of the summation of the relay' operating times; however, the chance of convexity of the problem will be decreased. This means the program gives a feasible solution after several unsuccessful executions with long runtime. While using the NS method proposed in this paper, feasible solutions to the problem is usually found in the first run, and the runtime of the problem is reduced significantly. Therefore, the proposed method is very helpful in coordination of the DOCRs in large networks where protection specialist cannot find a fair coordination of the relays by conventional analytical methods.

7. LIST OF SYMBOLS AND ABBREVIATIONS

7.1. *Symbols*

t_i^N	relay i operation time for Near-End fault
t_i^F	relay i operation time for Far-End fault
α_i	weight factor for relay i (considered to be 1 for all relays)
t_j^N	backup relay j operation time for Near-End fault
t_i^N	primary relay i operation time for Near-End fault
t_j^N	backup relay j operation time for Far-End fault
t_i^F	primary relay i operation time for Far-End fault
$TMS_{i,min}$	minimum allowed TMS for relay R_i
$TMS_{i,max}$	maximum allowed TMS for relay R_i
TMS_i	TMS of relay R_i
$Ip_{i,min}$	minimum value of relay R_i pick-up
$Ip_{i,max}$	maximum value of relay R_i pick-up
Ip_i	relay R_i pick-up current
$t^s_{far^t}$	i_{th} disregarded main relay operation time due to far end faults
$t^s_{near^t}$	i_{th} disregarded main relay operation time due to near end faults
$t^{m1}_{far^t}$	operation time of first back up relay of i_{th} disregarded main relay due to far end faults
$t^{m2}_{far^t}$	operation time of second back up relay of i_{th} disregarded main relay due to far end faults
$t^{m1}_{near^t}$	operation time of first back up relay of i_{th} disregarded main relay due to near end faults
$t^{m2}_{near^t}$	operation time of second back up relay of i_{th} disregarded main relay due to near end faults

7.2. *Abbreviations*

DOCR	Directional overcurrent relay
PS	Plug setting
TMS	Time multiplier setting
TCC	Time-current curve
GA	Genetic algorithm
min Z	Objective function
CTI	Coordination time interval
NI	Normally inverse
VI	Very inverse
EI	Extremely inverse
NS	Network splitting
R.No	Relay number

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APPENDIX

Data for 30-bus IEEE test system are given in Tables A1–A3. The data is on 100 MVA base and 132 kV, and 11 kV parts are modeled as external infeeds.

Table A1. Line parameter of 30-bus system (only 33 kV section).

Line	From bus	To bus	R(p.u)	X(p.u)	Rating(p.u)
1	12	14	0.1231	0.2559	0.32
2	12	15	0.0662	0.1304	0.32
3	12	16	0.0945	0.1987	0.32
4	14	15	0.221	0.1997	0.16
5	16	17	0.0824	0.1932	0.16
6	15	18	0.107	0.2185	0.16
7	18	19	0.0639	0.1292	0.16
8	19	20	0.034	0.068	0.32
9	10	20	0.0936	0.209	0.32
10	10	17	0.0324	0.0845	0.32
11	10	21	0.0348	0.0749	0.3
12	10	22	0.0727	0.1499	0.3
13	21	22	0.0116	0.0236	0.3
14	15	23	0.1	0.202	0.16
15	22	24	0.115	0.179	0.3
16	23	24	0.132	0.27	0.16
17	24	25	0.1885	0.3292	0.3
18	25	26	0.2544	0.38	0.3
19	25	27	0.1093	0.2087	0.3
20	28	27	0	0.396	0.3
21	27	29	0.2198	0.4153	0.3
22	27	30	0.3202	0.6027	0.3
23	29	30	0.2399	0.4533	0.3

Table A2. 30-bus system infeed data.

Infeed	Bus	Sk″(p.u)	R/X
1	10	4.79	0.09
2	12	0.621	0.07
3	27	1.982	0.12

Table A3. 30-bus system shunt capacitor data.

Capacitor	Bus	Susceptance
1	10	19
2	24	4

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