Optimal Coordination of Distance and Directional Overcurrent Relays Considering Different Network Topologies

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Abstract: Most studies in relay coordination have focused solely on coordination of overcurrent relays while distance relays are used as the main protection of transmission lines. Since, simultaneous coordination of these two types of relays can provide a better protection, in this paper, a new approach is proposed for simultaneous coordination of distance and directional overcurrent relays (D&DOCRs). Also, pursued by most of the previously published studies, the settings of D&DOCRs are usually determined based on a main network topology which may result in mis-coordination of relays when changes occur in the network topology. In the proposed method, in order to have a robust coordination, network topology changes are taken into account in the coordination problem. In the new formulation, coordination constraints for different network topologies are added to those of the main topology. A complex nonlinear optimization problem is derived to find the desirable relay settings. Then, the problem is solved using hybridized Genetic Algorithm (GA) with Linear Programming (LP) method (HGA). The proposed method is evaluated using the IEEE 14-bus test system. According to the results, a feasible and robust solution is obtained for D&DOCRs coordination while all constraints, which are due to different network topologies, are satisfied.

Keywords: Different Network Topologies, Directional Overcurrent Relay, Distance Relay, Relay Coordination, Robust Coordination.

1 Introduction

Generally, distance relays are used as the primary protection in transmission and sub-transmission systems. On the other hand, Directional Overcurrent Relays (DOCRs) are the primary protection in distribution systems and also serve as the backup protection in transmission and sub-transmission systems. Protection system should be able to detect and isolate the faulty part of the network as fast and selective as possible. In order to achieve these goals, protective relay coordination should be carried out. For effective coordination of D&DOCRs, usually three sets of parameters, including operating time of the second zone of distance relays (T_Zs), pickup current settings (I_{set}s), and time multiplier settings (*TMS*s) of DOCRs, should be determined. Until now, numerous studies have been published on DOCRs and D&DOCRs coordination [1–26]. A brief review is given in the following.

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In [1], DOCRs coordination problem is formulated with considering lines outages and the *TMS*s of DOCRs are determined for a fixed set of I_{set} values. In [2], a method is proposed to update the optimal settings of some DOCRs when network topology is changed due to line additions, where *TMS*s of DOCRs are calculated using LP method. The effect of dynamic changes in network topology is considered in [3] for calculation of the optimal settings of DOCRs, where LP method is used to calculate the *TMS*s of the relays. In [4], the impact of dynamic changes in network topology on the optimal settings of DOCRs is analyzed and several indices are introduced to determine the dynamic changes that have the greatest impact on fault currents. In [5–6], the effect of transmission line outages on DOCRs coordination is investigated. Based on the presented results, DOCRs coordination constraints are not satisfied in case of line outages, if relays settings were selected based on a fixed topology. Using LP and GA, a hybrid algorithm is proposed for solving the problem in [5]. In [6], DOCRs coordination problem is formulated as an interval linear programming problem and then is solved using interval arithmetic. A new approach for DOCRs coordination in a micro-grid system is developed in [7] to obtain robust settings for

DOCRs when micro-grid operates in both grid-connected and islanded modes, where hybrid Particle Swarm Optimization (PSO) is employed to solve the problem. Direction of the power flow and fault current could be changed when distributed generators are connected to a network. This issue is considered in [8] in the DOCRs coordination problem for proper operation of relays, where differential evolution algorithm is used to solve the problem. The same idea as in [5–6] is proposed in [9], and the problem is solved using LP and PSO as another hybrid algorithm.

In [10], coordination of D&DOCRs is analyzed for different protection schemes. In these schemes, the optimal values of *TMS*s are calculated using LP method considering specific values for T_{Z2}s and I_{set}s. It is found that T_{Z2}s should be set at 1.1 seconds to have a selective protection in combined coordination of these relays. In [11], DOCRs coordination problem is investigated considering the coordination constraints imposed by distance and breaker failure relays, and LP method is used to solve the problem. Furthermore, specific values are assumed for I_{set}s, T_{Z2}s, and the operating time of the breaker failure relays. In [12], coordination problem for D&DOCRs is solved using an evolutionary algorithm in which the operating times of the second and third zones of distance relays are treated as optimization variables. Optimal values such as 1 and 1.98 seconds are obtained for the operating times of these zones. T_{Z2} is introduced as a new variable in [13] which is the same for all distance relays. The optimal T_{Z2} and *TMS*s are calculated using LP method for a predetermined set of I_{set}s. Based on the reported results, optimal values such as 0.98 seconds are obtained for T_{Z2} to satisfy the coordination constraints. Several LP methods, including dual simplex, path following, and homogeneous self-dual methods are used to calculate the optimal T_{Z2}s and *TMS*s for D&DOCRs coordination in [14], while both cases of identical and different T_{Z2} values are considered. Changing the operating characteristic of the backup DOCRs is suggested to have rational values for T_{Z2}s in D&DOCRs coordination [15]. The change is performed with respect to the fault location and current, adaptively. The optimal values for *TMS*s are determined by assuming specific values for T_{Z2}s and I_{set}s. In [16-18], new Objective Functions (*OF*s) are presented for D&DOCRs coordination problem. In these studies, I_{set}s and T_{Z2}s are assumed to be predetermined, and GA is employed to calculate the optimal *TMS*s. In [17, 18], specific operating characteristics are considered for DOCRs, whereas in [16], GA selects the best operating characteristics from a set of available ones. A new *OF* is proposed in [19] to determine the optimal values of T_{Z2}s and *TMS*s, while I_{set}s are predetermined. Furthermore, selection of the best operating characteristics for DOCRs is modeled as a decision variable in the optimization problem which is solved by GA. In [20] and [21], D&DOCRs coordination problem is solved using HGA and hybrid PSO, respectively, while different T_{Z2}s are assumed for distance relays. D&DOCRs coordination problem is solved using a combined approach, based on LP and PSO by considering constant values for T_{Z2}s in [22]. A new formulation is proposed in [23] for D&DOCRs coordination in power systems with series compensated lines, and modified adaptive PSO is used to solve the problem. In [24], D&DOCRs coordination problem is modeled by considering the discrimination time between the operating times of the backup DOCRs and T_{Z2}s of primary distance relays in the *OF* to decrease these times simultaneously. Furthermore, the problem is solved by multiple embedded crossovers PSO. In [25], the effect of pilot protection on the optimal settings of D&DOCRs is investigated. Based on the presented results, it can be seen that the overall operating time of the protection system is reduced considering pilot protection in the relay coordination.

Based on the literature review, the effect of network topology changes is only considered in overcurrent relays coordination. No study has investigated the influence of the changes in the network topology on the simultaneous coordination of distance and overcurrent relays. This may lead to the unwanted/non-operation of D&DOCRs when a fault occurs in the network. Therefore, to achieve robust settings for D&DOCRs, the effect of changes in network topology should also be considered in simultaneous coordination of these two types of relays. But, considering topology changes results in a significant increase in the number of constraints. Recently, in [26], which is the only study that is done in the subject of topology changes effect on D&DOCRs coordination; new theorems are proved which help reduce the complexity of coordination problem, by identifying/eliminating the redundant constraints before attempting to solve the problem.

Generally, D&DOCRs coordination is a nonlinear optimization problem. The reason behind the nonlinearity is the I_{set}. But, if I_{set}s are known, the problem is then converted to a linear one. However, assuming predetermined I_{set}s and solving the problem using LP method, as in [26], the solution may not be globally optimal. Therefore, I_{set}s should be considered as optimization variables. Thus, to provide proper operation of D&DOCRs, this paper focuses on determination of globally optimal and robust settings for D&DOCRs, by considering different network topologies. Here, it is assumed that the topology changes are due to single line outages. In this paper, HGA are used to determine the optimal settings of D&DOCRs. Specifically, GA is used to search for the best possible values of I_{set}s and then LP method is applied to solve the problem for every single set of I_{set} values provided by the heuristic search. The obtained results indicate that, by using the proposed method, an effective and feasible solution for T_{Z2}s, *TMS*s, and I_{set}s can be achieved.

2 Proposed Formulation for D&DOCRS Coordination Problem

The aim of relay coordination is to determine the optimal settings of relays such that the sum of the operating times of the primary relays is minimized, while coordination constraints are satisfied. In this section, first, an *OF* is introduced to be used for the optimization. Then, the D&DOCRs coordination constraints are explained for the main network topology. Finally, the constraints are extended to consider the impact of different network topologies on the optimal settings.

2.1 Objective Function for D&DOCRS Coordination Problem

In this paper, the operating times of the second zone of distance relays, in addition to pickup current and time multiplier settings of DOCRs are considered as optimization variables. The following *OF* is used to calculate the optimal settings:

$$OF = \sum_{i=1}^{n} t_i + \sum_{j=1}^{m} T_{Z2j} \tag{1}$$

The operating characteristics of DOCRs can be represented by different linear and nonlinear functions. In the present study, very inverse characteristic is utilized based on the IEC standard,

$$t = \frac{13.5 \times TMS}{\left(\frac{I_{fault}}{I_{set}}\right) - 1} \tag{2}$$

2.2 D&DOCRS Coordination Constraints in the Main Network Topology

D&DOCRs coordination constraints are divided into two groups, including those related to the selectivity of the protection system, and those related to the limits on the relay parameters.

2.2.1 Selectivity Constraints

In order to have a selective protection system, the operating time of the backup relays should be greater than that of their respective primary ones. The minimum operating time of the backup relays are determined by the operating time of the primary relays, the operating time of the circuit breaker, and the overshoot time. To achieve a selective protection in D&DOCRs coordination, not only the selectivity should be maintained between the DOCRs, but it also should be held between them and the distance relays. Based on Fig. 1, the coordination constraints of DOCRs for the near-end and far-end faults are expressed as:

$$\begin{aligned} t_b^{F_1} - t_p^{F_1} &\geq CTI \\ t_b^{F_2} - t_p^{F_2} &\geq CTI \end{aligned} \tag{3}$$

Moreover, as shown in Fig. 2, to maintain the selectivity between D&DOCRs, the operating time of the backup DOCRs should be longer than that of the second zone of their respective primary distance relays. Furthermore, the operating time of the second zone of the backup distance relays should be longer than that of their respective primary DOCRs. These are formulated in Eq. (4):

$$\begin{aligned} t_b^{F_4} - T_{Z2p} &\geq CTI' \\ T_{Z2b} - t_p^{F_3} &\geq CTI' \end{aligned} \tag{4}$$

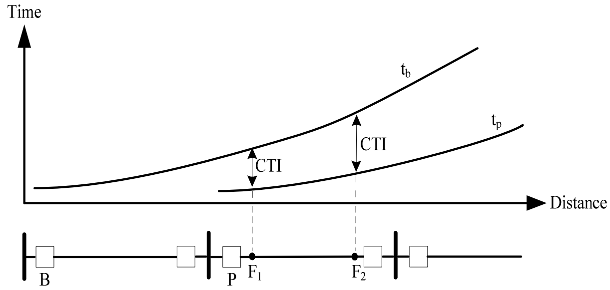

Fig. 1 Selectivity illustration for overcurrent relays.

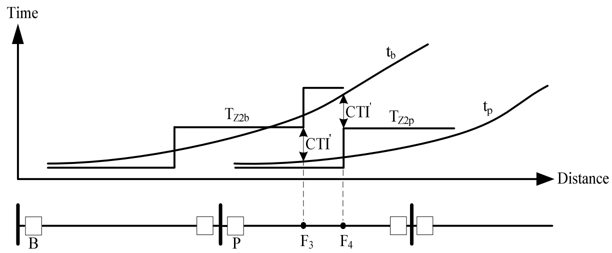

Fig. 2 Selectivity illustration for distance and overcurrent relays.

2.2.2 Relay Settings Constraints

Settings of DOCRs are bounded between lower and upper limits based on the following inequalities:

$$\begin{aligned} &TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \\ &max\left(I_{load_i}^{max}, I_{set_i}^{min}\right) \leq I_{set_i} \leq min\left(I_{fault_i}^{min}, I_{set_i}^{max}\right) \end{aligned} \tag{5}$$

2.3 D&DOCRs Coordination Constraints Considering Different Network Topologies

Network topology may change under planned or unplanned events such as maintenance activities or fault occurrence in the network. Line outage, generation unit outage, adding new line, adding new generation unit, etc., cause change in network topology. These changes in topology lead to changes in the network impedance matrix and fault currents magnitude and distribution. In these situations, relays may have inappropriate operations and the selectivity of protection system can be degraded. Therefore, in order to have a selective protection system, changes in topology should be considered in the calculation of the relay optimal settings. By considering the possibility of different network topologies in D&DOCRs coordination, Eqs. (3) and (4) are extended to Eqs. (6) and (7), respectively:

$$t_{bs}^{F_1} - t_{ps}^{F_1} \geq CTI \qquad s \in S \qquad (6)$$
$$t_{bs}^{F_2} - t_{ps}^{F_2} \geq CTI$$

$$t_{bs}^{F_4} - T_{Z2p} \geq CTI' \qquad s \in S \qquad (7)$$
$$T_{Z2b} - t_{ps}^{F_3} \geq CTI'$$

In the above inequalities, S is the set of all topologies which are taken into account in relay coordination. In other words, many new constraints related to each network topology are added to the constraints of the main topology, in order to achieve robust optimal settings for D&DOCRs. This results in a significant increase in the coordination problem complexity.

3 Solving the D&DOCRs Coordination Problem

Based on the formulations presented in Section 2, D&DOCRs coordination is a nonlinear optimization problem. Actually, I_{set} parameter causes nonlinearity in the operating characteristics of DOCRs, which mainly results in a nonlinear optimization problem. In this paper, to handle the mentioned nonlinearity, a hybrid optimization algorithm is considered in order to obtain the optimal settings of the relays (T_{Z2}s, *TMS*s, and I_{set}s). The HGA algorithm which is proposed in [5] is used with some modifications to obtain the optimal settings of D&DOCRs. It is worth noting that convergence of HGA is much faster than conventional GA [5]. The difference becomes more obvious when the complexity of the system under study is increased. Fig. 3 shows the flowchart of the proposed modified HGA.

The algorithm is explained, based on Fig. 3, as follows:

***Step 1*:** For each DOCR, a random I_{set} is selected in accordance with the boundaries of the relay pickup current in Eq. (5). Upon determining the I_{set}s, the nonlinear optimization problem is converted to a linear one.

***Step 2*:** LP method is used to solve the linear optimization sub-problem, and T_{Z2}s and *TMS*s are obtained for all D&DOCRs, if the LP sub-problem converges. If the sub-problem does not converge for some values of I_{set}s, a large penalty value is added to the *OF*. The LP sub-problem is called repeatedly by the GA routine.

***Step 3*:** The *OF* is evaluated and then GA operators (selection, crossover, and mutation) are applied to create the next generation. The process is terminated after a fixed number of iteration which depends on the generation population and the complexity of the system under study.

4 Simulation Results

For a comprehensive analysis, first, the importance of considering distance relays along with DOCRs for relay coordination in an interconnected power system is discussed. Second, the importance of including network topology changes in computation of the optimal settings of D&DOCRs is revealed. Finally, in the third analysis, changes in network topology are considered for determination of the optimal settings.

In this study, the IEEE 14-bus test system which is shown in [25-26], is used to perform the analysis. The test system consists of five synchronous machines (two synchronous generators and three synchronous compensators), three transformers and sixteen lines. The system data is taken from [27]. The lines are protected by distance and overcurrent relays (32 distance relays, and 32 overcurrent relays). *TMS*s are considered as continuous variables in the range of 0.05 to 1.1, and *CTI*s and *CTI'*s are assumed to be 0.2 seconds. I_{set}s of all DOCRs are considered as discrete values in the range of 2.5 to 12.5 amperes, with the steps of 1.25 amperes. The reason is that the nominal secondary current of the current transformers is assumed to be 5 amperes. Furthermore, the fault currents for relay coordination are calculated at the near-end fault of the relays, the end of the first zone of the primary distance relays (point F_1 in Fig. 1), i.e., 80 % of the line length (point F_3 in Fig. 2), and at the end of the second zone of the backup distance relay, i.e., 50 % of the shortest line protected by the primary distance relays (point F_4 in Fig. 2).

4.1 Importance of Simultaneous Coordination of Distance and Overcurrent Relays

In this subsection, in order to analyze the importance of simultaneous coordination of D&DOCRs, the optimal settings of DOCRs are calculated with and without considering distance relays.

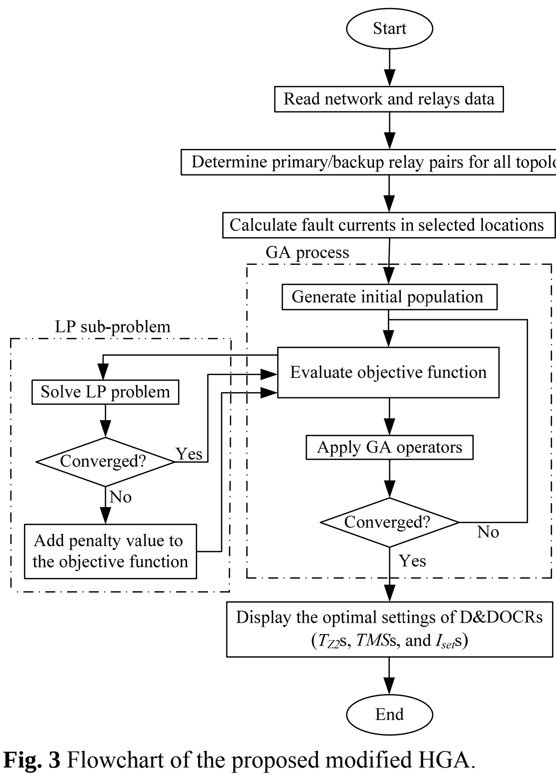

Fig. 3 Flowchart of the proposed modified HGA.

The optimal settings of the D&DOCRs for the main network topology are presented in Table 1, when these two types of relays are considered simultaneously in the coordination problem. The problem has 96 variables (32 T_{Z2}s, 32 *TMS*s, and 32 I_{set}s), as well as 186 selectivity constraints. Based on the presented results in Table 1, the *OF*, the sum of the operating times of the DOCRs, and the average of T_{Z2}s are 16.0565, 3.4469, and 0.3941 seconds, respectively.

The convergence process of HGA for the problem for main network topology is shown in Fig. 4.

Table 2 presents the optimal settings for the DOCRs without considering distance relays. Fig. 5 shows the convergence process of HGA for DOCRs coordination problem for main network topology. By comparing the results in Tables 1 and 2, it can be seen that the sum of the operating times of all DOCRs decreases when DOCRs are coordinated without considering distance relays. However, this may lead to the loss of selectivity when these settings are applied to the DOCRs installed in an interconnected power system.

In order to assess the applicability of the obtained optimal settings for D&DOCRs, three indices are defined in Eq. (8) based on Fig. 6. The positive values for these indices indicate the satisfaction of associated constraints and the negative ones represent the violation of associated constraints.

$$\begin{aligned} CV_{ox} &= t_{obx} - t_{opx} - CTI \\ CV_{ozh} &= t_{obZ2h} - T_{Z2p} - CTI' \\ CV_{zoy} &= T_{Z2b} - t_{opZ2y} - CTI' \end{aligned} \tag{8}$$

Table 1 Optimal settings of D&DOCRs for the main network topology.

Relay No.	I_{set}	*TMS*	T_{Z2}	Relay No.	I_{set}	*TMS*	T_{Z2}
1	5	0.0500	0.3286	17	12.5	0.1226	0.5511
2	10	0.0500	0.3881	18	12.5	0.0533	0.4048
3	5	0.0500	0.3286	19	12.5	0.0599	0.3525
4	10	0.0500	0.3881	20	6.25	0.0500	0.4277
5	7.5	0.0500	0.4040	21	12.5	0.1081	0.4071
6	10	0.0500	0.3881	22	12.5	0.0600	0.4778
7	6.25	0.0519	0.4185	23	12.5	0.1813	0.4367
8	12.5	0.0544	0.3286	24	12.5	0.1658	0.4105
9	5	0.0673	0.4183	25	12.5	0.0643	0.4444
10	7.5	0.0500	0.3286	26	12.5	0.1413	0.4932
11	8.75	0.0527	0.4040	27	12.5	0.0804	0.3867
12	6.25	0.0500	0.3286	28	12.5	0.1551	0.4615
13	12.5	0.1072	0.4183	29	11.25	0.0514	0.3583
14	7.5	0.0561	0.3207	30	11.25	0.0517	0.3000
15	12.5	0.1471	0.3758	31	12.5	0.0720	0.4841
16	6.25	0.0734	0.3368	32	12.5	0.0672	0.3094
OF				16.0565			
$\sum_{i=1}^{n} t_i$				3.4469			
Average of T_{Z2}s				0.3941			

Table 2 Optimal settings of DOCRs for the main network topology without considering distance relays.

Relay No.	I_{set}	*TMS*	Relay No.	I_{set}	*TMS*
1	5	0.0500	17	12.5	0.1140
2	10	0.0500	18	12.5	0.0533
3	5	0.0500	19	12.5	0.0600
4	10	0.0500	20	6.25	0.0500
5	7.5	0.0500	21	12.5	0.1084
6	10	0.0500	22	12.5	0.0583
7	6.25	0.0505	23	12.5	0.1813
8	12.5	0.0544	24	12.5	0.1583
9	5	0.0673	25	12.5	0.0557
10	7.5	0.0500	26	11.25	0.1606
11	8.75	0.0522	27	12.5	0.0805
12	6.25	0.0500	28	12.5	0.1357
13	12.5	0.0994	29	11.25	0.0515
14	7.5	0.0561	30	11.25	0.0517
15	12.5	0.1471	31	12.5	0.0724
16	7.5	0.0579	32	11.25	0.0527
$\sum_{i=1}^{n} t_i$			3.3230		

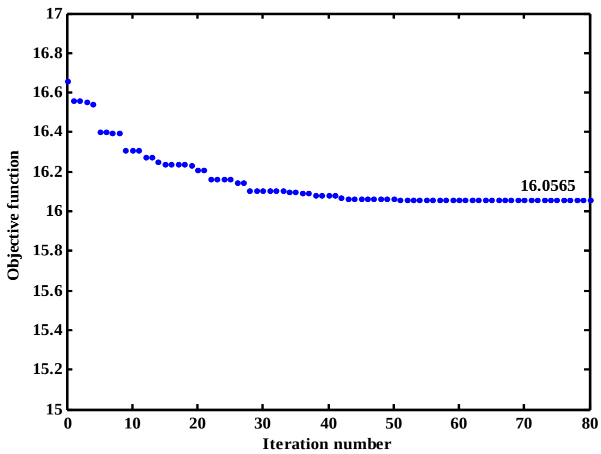

Fig. 4 Convergence of HGA for D&DOCRs coordination problem for main network topology.

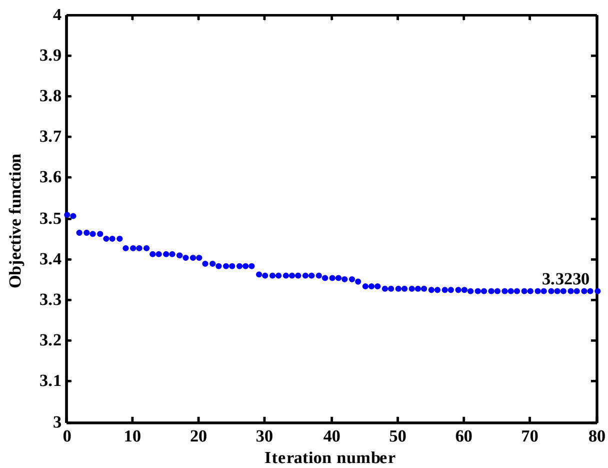

Fig. 5 Convergence of HGA for DOCRs coordination problem for main network topology.

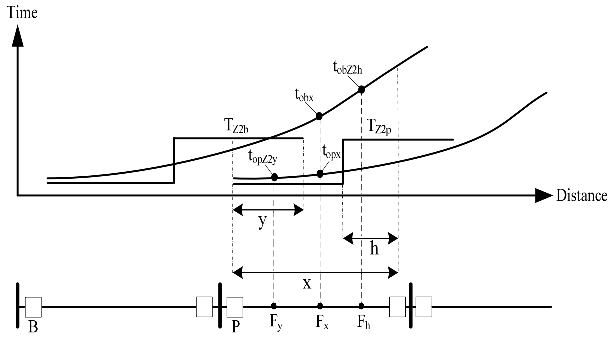

Fig. 6 Fault location illustration for the calculation constraint value.

The values of the constraints are calculated for the analysis of selectivity in the case that the DOCRs are coordinated without considering the distance relays. These values are presented in Table 3, based on the settings of the DOCRs summarized in Table 2, and the value of 0.3941 seconds for the T_{Z2}s of all distance relays. It is worth noting that any value in the typical range of T_{Z2} (i.e., 0.3–0.6 seconds) can be selected for T_{Z2}s of the distance relays when these two types of relays are independently coordinated. In this analysis, the average of T_{Z2}s (0.3941 seconds based on Table 1) is selected for operating times of the second zone of the distance relays. The values of the constraints are computed for the near-end faults (CV_{on}), the faults at the end of the second zone of the backup distance relays ($CV_{zo50\%}$; 50% of the shortest line length, i.e., point F_y in Fig. 6), and the faults at the beginning of the second zone of the primary distance relays ($CV_{oz80\%}$; 80% of the line length, i.e., point F_h in Fig. 6). In Table 3, negative values indicate the violated constraints.

According to Table 3, it can be seen that 20 out of 92 active constraints between primary/backup distance and overcurrent relays, i.e., 21.51% of total active constraints, are violated when the distance relays and DOCRs are coordinated independently, which is considerable. Therefore, for proper relay coordination in an interconnected power system, these relays should be coordinated simultaneously.

4.2 Importance of Considering Network Topology Changes on D&DOCRS Coordination

In order to demonstrate the importance of considering network topology changes in D&DOCRs coordination, the constraints values are investigated as performance indices. These are calculated for cases in which a change occurs in the network topology while the D&DOCRs are configured with the optimal settings obtained for the main topology.

For example, Table 4 presents the values of the constraints in case of the outage of line 5. Results of Table 4 are obtained according to the optimal settings presented in Table 1. Based on the results in Table 4, it can be concluded that 37 out of 127 active constraints, i.e., 29.13 % of total active constraints, are violated, which is significant. It is worth noting that violation of the constraints also occurs after the outage of other lines, if D&DOCRs are configured based on the optimal settings obtained only for the main network topology. Therefore, it is important to include the effect of network topology changes in computation of the optimal settings.

4.3 D&DOCRs Optimal Settings Considering Network Topology Changes

In order to have robust coordination against topology changes, the optimal settings are computed considering different topologies made by single line outages. These settings are shown in Table 5.

By considering 16 different network topologies for every possible single line outage, as well as the main topology, the number of coordination constraints is increased from 186 to 2790.

Table 3 Values of constraints in D&DOCRs coordination for the main network topology by assuming independent coordination of distance and overcurrent relays.

Relay No.		Value of constraint			Relay No.		Value of constraint		
PR	BR	CV_{on}	$CV_{oz8\%}$	$CV_{zo50\%}$	PR	BR	CV_{on}	$CV_{oz80\%}$	$CV_{zo5\%}$
1	4	0.025	--	0.006	12	5	0.549	--	0.132
1	6	0.356	--	0.006	12	15	0.028	1.047	0.081
2	3	0.74	--	0.065	13	7	0	--	-0.008
2	8	0	-0.003	0.065	14	9	0.106	--	0.113
2	10	0.227	11.118	0.065	14	16	0	1.022	0.057
2	12	0.149	--	0.065	15	9	0	0.237	-0.024
3	2	0.025	--	0.006	15	13	0	-0.06	-0.024
3	6	0.356	--	0.006	16	5	0.442	1.391	-0.007
4	1	0.74	--	0.065	16	11	0	0.117	-0.007
4	8	0	-0.003	0.065	17	20	0.591	--	-0.018
4	10	0.227	11.118	0.065	17	22	0	--	-0.064
4	12	0.149	--	0.065	18	27	0	0.064	0.007
5	2	0.025	--	0.034	19	18	0.055	1.943	0.087
5	4	0.025	--	0.034	19	22	0.069	--	0.06
6	11	0.079	--	0.097	20	30	0	0.853	0.141
6	15	0	0.631	0.018	21	18	0	1.134	-0.011
7	1	0.74	--	0.089	21	20	0.605	--	-0.011
7	3	0.74	--	0.089	22	29	0.046	--	0.088
7	10	0.226	--	0.089	22	32	0.002	-0.149	0.088
7	12	0.148	--	0.089	23	26	0	0.164	-0.099
8	14	0	--	0.073	24	28	0	-0.06	-0.056
9	1	0.74	--	0.082	25	24	0	0.755	0.012
9	3	0.74	--	0.082	26	31	0	0.265	-0.092
9	8	0	--	0.082	27	23	0	0.063	-0.043
9	12	0.149	--	0.082	28	17	0	0.185	-0.113
10	13	0.115	1.308	0.122	29	19	0	0.328	0.041
10	16	0.009	--	0.059	30	21	0.045	0.536	0.06
11	1	0.745	--	0.09	30	32	0	0.112	0.095
11	3	0.745	--	0.09	31	21	0	0.491	-0.014
11	8	0.005	2.687	0.09	31	29	0	1.475	0.035
11	10	0.232	--	0.09	32	25	0	0.233	0.026

PR and BR indicate primary and backup relays, and (--) indicates inactive constraints set.

Table 4 Values of constraints in D&DOCRs coordination after the outage of line 5, based on the optimal settings for the main network topology.

Relay No.		Value of constraint			Relay No.		Value of constraint		
PR	BR	CV_{on}	$CV_{oz80\%}$	$CV_{zo50\%}$	PR	BR	CV_{on}	$CV_{oz80\%}$	$CV_{zo50\%}$
1	4	0.044	--	0.002	15	13	-0.091	-0.088	-0.079
1	6	0.286	--	0.002	16	5	0.315	0.6	0.026
2	3	0.565	--	-0.007	16	11	-0.049	-0.101	0.026
2	8	-0.033	-0.089	-0.007	17	20	0.654	--	-0.002
2	12	0.011	1.565	-0.007	17	22	0.014	--	-0.003
3	2	0.044	--	0.002	18	27	0.005	0.08	-0.005
3	6	0.286	--	0.002	19	18	0.069	2.387	0.096
4	1	0.565	--	-0.007	19	22	0.094	--	0.143
4	8	-0.033	-0.089	-0.007	20	30	0.002	0.877	0.046
4	12	0.011	1.565	-0.007	21	18	0.014	1.389	-0.002
5	2	0.042	--	0.028	21	20	0.679	--	0.021
5	4	0.042	--	0.028	22	29	0.046	--	0.047
6	11	0.014	--	0.101	22	32	0.139	0.033	-0.002
6	15	0.07	0.483	-0.004	23	26	-0.004	0.131	-0.009
7	1	0.563	--	0.016	24	28	0.052	0.007	-0.003
7	3	0.563	--	0.016	25	24	-0.001	0.726	-0.005
7	12	0.008	--	0.016	26	31	0.002	0.175	-0.002
8	14	0.013	--	0.002	27	23	0.006	0.087	-0.006
11	1	0.569	--	0.021	28	17	0.002	0.186	-0.003
11	3	0.569	--	0.021	29	19	0.002	0.375	-0.001
11	8	-0.03	--	0.021	30	21	0.046	0.633	0.072
12	5	0.407	--	0.138	30	32	0.14	0.668	0.009
12	15	0.099	0.476	0.063	31	21	0.002	0.409	-0.001
13	7	-0.01	--	0.007	31	29	0.002	1.431	-0.001
14	16	-0.067	0.296	-0.017	32	25	0.005	0.476	-0.004

Table 5 Optimal settings of D&DOCRs with considering different network topologies.

Relay No.	I_{set}	*TMS*	T_{Z2}	Relay No.	I_{set}	*TMS*	T_{Z2}
1	5	0.0500	0.4208	17	12.5	0.1565	0.6983
2	12.5	0.0581	0.4228	18	12.5	0.0756	0.4934
3	5	0.0500	0.4208	19	12.5	0.1379	0.9330
4	12.5	0.0581	0.4228	20	6.25	0.1359	0.5012
5	7.5	0.0500	0.5953	21	12.5	0.1452	0.4910
6	10	0.0500	0.4208	22	11.25	0.1095	0.5626
7	7.5	0.0500	0.5110	23	12.5	0.2140	0.5032
8	12.5	0.0841	0.4066	24	12.5	0.2146	0.5436
9	8.75	0.0500	0.5969	25	12.5	0.0924	0.6863
10	6.25	0.0563	0.4208	26	12.5	0.1998	0.5917
11	12.5	0.0531	0.5582	27	12.5	0.0977	0.4780
12	6.25	0.0533	0.4208	28	12.5	0.2158	0.5465
13	12.5	0.1521	0.5652	29	12.5	0.2102	0.8160
14	8.75	0.0509	0.3901	30	2.5	0.3638	0.4308
15	8.75	0.2701	0.3979	31	10	0.1208	0.8955
16	3.75	0.1785	0.3687	32	12.5	0.1296	0.6583
OF				22.2997			
$\sum_{i=1}^{n} t_i$				5.1306			
Average of T_{Z2}s				0.5365			

The convergence process of HGA for D&DOCRs coordination problem considering different network topologies is shown in Fig. 7. By comparing Tables 1 and 5, it can be seen that the optimal setting values are increased when considering different topologies to obtain robust coordination. In this case, the *OF*, the sum of the operating times of the DOCRs, and the average of T_{Z2}s are increased from 16.0565, 3.4469, and 0.3941 seconds, to 22.2997, 5.1306, and 0.5365 seconds, respectively. It is worth noting that the robust settings satisfy all constraints.

In order to investigate the proper fault clearing function with the settings of Table 5, the values of the constraints are computed for different fault locations after the outage of line 5, which are presented in Table 6. These values are computed for the faults occurring at 10% of the line length ($CV_{o10\%}$) in order to analyze the selectivity constraints between the DOCRs. Moreover, in order to investigate the selectivity constraints between the distance and overcurrent relays, the values of the constraints are computed for two arbitrary points in the protection zones. These points are selected to be at the second zone of the backup distance relays, just before the end of the zone (e.g., 30% of the line length, point F_y in Fig. 6; $CV_{zo30\%}$), and at a point in the second zone of the primary distance relays (e.g., 95% of the line length, point F_h in Fig. 6; $CV_{oz95\%}$). According to Table 6, all values of constraints are positive. Therefore, all active selectivity constraints are satisfied when line 5 is out of service. The same results are obtained for other single line outages and fault locations. Based on the above explanations, the robust settings are obtained for the protection system when the D&DOCRs are configured based on Table 5.

Table 6 Values of constraints in D&DOCRs coordination after the outage of line 5, based on the optimal settings in Table 5.

Relay No.		Value of constraint			Relay No.		Value of constraint		
PR	BR	$CV_{10\%}$	$CV_{oz95\%}$	$CV_{zo30\%}$	PR	BR	$CV_{10\%}$	$CV_{oz95\%}$	$CV_{zo30\%}$
1	4	0.514	--	0.085	15	13	0.009	0.136	0.023
1	6	0.433	--	0.083	16	5	0.297	0.699	0.17
2	3	4.319	--	0.07	16	11	0.143	0.371	0.133
2	8	0.109	0.145	0.056	17	20	5.379	--	0.055
2	12	0.06	4.776	0.07	17	22	0.383	--	0.081
3	2	0.514	--	0.085	18	27	0.039	0.366	0.042
3	6	0.433	--	0.083	19	18	0.26	5.507	0.089
4	1	4.319	--	0.07	19	22	7.594	--	0.124
4	8	0.109	0.145	0.056	20	30	0.02	1.738	0.113
4	12	0.06	4.776	0.07	21	18	0.192	4.631	0.067
5	2	0.527	--	0.093	21	20	--	--	0.075
5	4	0.527	--	0.093	22	29	1.442	--	0.467
6	11	0.538	--	0.264	22	32	0.518	0.812	0.309
6	15	0.225	0.624	0.061	23	26	0.164	0.511	0.065
7	1	1.142	--	0.113	24	28	0.185	0.162	0.022
7	3	1.142	--	0.113	25	24	0.102	1.67	0.102
7	12	0.132	--	0.113	26	31	0.033	0.416	0.338
8	14	0.109	--	0.048	27	23	0.058	0.202	0.049
11	1	1.35	--	0.092	28	17	0.052	0.472	0.065
11	3	1.35	--	0.092	29	19	0.081	2.414	0.148
11	8	0.169	--	0.077	30	21	0.184	1.412	0.141
12	5	0.791	--	0.33	30	32	0.61	1.969	0.332
12	15	0.239	0.643	0.106	31	21	0.136	0.712	0.071
13	7	0.127	--	0.074	31	29	1.574	41.285	0.431
14	16	0.035	0.596	0.036	32	25	0.053	0.998	0.085

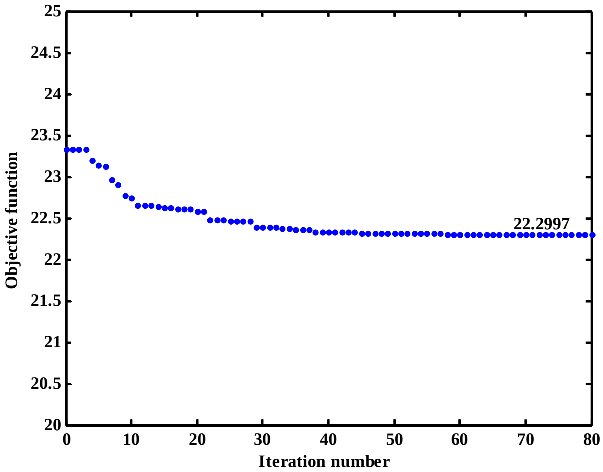

Fig. 7 Convergence of HGA for D&DOCRs coordination problem considering different network topologies.

4 Conclusion

In this paper, the importance of simultaneous D&DOCRs coordination and considering network topology changes in the D&DOCRs coordination are investigated. Furthermore, a new approach is proposed to obtain robust and applicable settings for D&DOCRs considering topology changes. In order to achieve this aim, all coordination constraints associated with different topologies made by single line outages, are added to the constraints of the main topology. D&DOCRs coordination problem is a nonlinear complex one that the complexity of the problem is increased by considering topology changes in the coordination. Hybrid linear programming method and genetic algorithm is used to solve the nonlinear problem. Based on the results, it can be concluded that the effect of changes in topology, as well as, simultaneous coordination of distance and overcurrent relays should be considered to have effective and robust optimal settings for these two types of relays.

Nomenclature

T_{Z2j}	Operating time of the second zone of the j^{th} distance relay;
T_{Z2p} and T_{Z2b}	Operating times of the second zone of primary and backup distance relays, respectively;
t_i	Operating time of the i^{th} DOCR for the near-end fault;
$t_p^{F_1}$ and $t_b^{F_1}$	Operating times of primary and backup DOCRs for the near-end fault, respectively;
$t_p^{F_2}$ and $t_b^{F_2}$	Operating times of primary and backup DOCR for the far-end fault, respectively;
$t_p^{F_3}$	Operating time of primary DOCRs for the fault at the end of the second zone of backup distance relays;
$t_b^{F_4}$	Operating time of backup DOCRs, for the faults at the end of the first zone of primary distance relays;
t_{opZ2y} and t_{opx}	Operating times of the primary DOCRs for the fault occurring at the point F_y in the range y located in the second zone of the backup distance relay, and at the point F_x in the range x, respectively;
t_{obZ2h} and t_{obx}	Operating times of the backup DOCRs for the fault at the point F_h in the range h located in the second zone of the primary distance relay, and at the point F_x in the range x, respectively;
TMS_i^{min} and TMS_i^{max}	Minimum and maximum available time multiplier settings of the i^{th} DOCR, respectively;
CTI	Coordination time interval between primary and backup DOCRs, typically between 0.2 to 0.5 seconds;
CTI'	Coordination time interval between distance and overcurrent relays, typically between 0.2 to 0.5 seconds, which may be different from CTI;
$I_{set_i}^{min}$ and $I_{set_i}^{max}$	Minimum and maximum available pickup current of the i^{th} DOCR, respectively;
$I_{load_i}^{max}$	Maximum load current passing through of the i^{th} DOCR;
I_{fault}	Fault current passing through DOCR;
$I_{fault_i}^{min}$	Minimum fault current passing through of the i^{th} DOCR;
n	Number of DOCRs;
m	Number of distance relays;
CV_{ox}	The value of the constraint between two DOCRs for the fault at the point F_x;
CV_{zoy}	The value of the constraint between backup distance and primary overcurrent relays for the fault at the point F_y;
CV_{ozh}	The value of the constraint between backup overcurrent and primary distance relays for the fault at the point F_h;

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