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Preprocessing of distance and directional overcurrent relays coordination problem considering changes in network topology

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SUMMARY

The number of constraints in coordination of distance and directional overcurrent relays (D&DOCRs) in power systems increases significantly by considering changes in network topology, especially in large power systems. By increasing the number of coordination constraints, the complexity of the D&DOCRs coordination problem is increased. Therefore, in this paper, a new method is proposed to reduce the number of coordination constraints in the D&DOCRs coordination problem. In the proposed method, redundant constraints are identified before solving the coordination problem. The proposed method is independent from D&DOCRs settings and operating characteristics of directional overcurrent relays. In order to evaluate the proposed method, two different test systems, namely, an 8-bus and the IEEE 14-bus test systems, are used. Based on the presented results, it can be seen that the proposed method is efficient, and by utilizing it, many redundant coordination constraints are identified and removed, helping to obtain effective solutions for the optimal settings with less computational effort. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: distance and overcurrent relays coordination; coordination constraints; changes in network topology; constraints reduction

1. INTRODUCTION

Protective relays coordination should be carried out in order to achieve selective and fast protection systems. Relay coordination problem in large and interconnected power systems is a very complicated one, because the number of coordination constraints is increased by the size of the power system. The complexity of this problem is multiplied by increasing the number of coordination constraints.

In transmission and subtransmission systems, distance relays are used as primary and directional overcurrent relays (DOCRs) and are also used as backup protection system. Three sets of parameters, including pickup current settings (I_{set}s) and time multiplier settings (*TMS*s) for overcurrent relays, and operating times of the second zones (T_{Z2}s) for distance relays should be usually determined in the D&DOCRs coordination problem.

Changes in network topology, because of planned or unplanned events such as maintenance activities or fault occurrences in network, are common events in modern power systems. Changes in network topology can occur because of inclusion or outage of transmission lines, power transformers, generation units, and so forth. These changes lead to changes in network impedance matrix and, consequently, fault currents distribution. Therefore, miscoordination can occur under these situations. As a result, in order to have selective protection and robust relay coordination, network topology changes should be considered in the relay coordination problem.

Up to now, changes in network topology have been modeled in the DOCRs coordination problem [1–8]. Transmission line outage has been considered in the DOCRs coordination problem in [1–4], where the problem has been solved using direct methods and decomposition techniques [1], hybrid

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linear programming (LP) and genetic algorithm (GA) [2], interval linear programming [3], and hybrid LP and particle swarm optimization (PSO) [4]. A method has been proposed in [5] to update the optimal settings of some DOCRs when transmission lines are added to the network. Effect of dynamic changes in network topology has been considered in [6,7]. In [8], robust settings for DOCRs in a microgrid have been determined using hybrid PSO, when the microgrid operates in both grid-connected and islanded modes.

The coordination problem for two types of relays, namely, distance and overcurrent relays, has been investigated in several research works such as [9–14]. The optimal *TMS*s have been determined using LP by considering prespecified T_{Z2}s, I_{set}s, and operating times of breaker failure relays in [9]. In [10], an evolutionary algorithm has been proposed for solving the problem, in which the operating times of the second and third zones of distance relays have been considered as optimization variables. The optimal T_{Z2} and *TMS*s for D&DOCRs have been computed, using T_{Z2} as the single optimization variable for all distance relays in [11]. In [12], a new objective function has been presented by assuming several operating characteristics for DOCRs. The best characteristic and the optimal T_{Z2}s and *TMS*s have been obtained using GA, by assuming specific I_{set}s. Effect of series compensation in transmission lines on the optimal settings of D&DOCRs has been analyzed in [13], where the problem has been solved using modified adaptive PSO. In [14], a new objective function has been developed for the coordination problem by considering discrimination time between operating times of backup DOCRs and T_{Z2}s of primary distance relays, in order to decrease these times simultaneously. Furthermore, the problem is solved by multiple-embedded crossovers PSO.

Based on the literature review, it can be concluded that the effect of network topology changes on the optimal settings, despite its importance, has not been considered in the D&DOCRs coordination problem. To achieve robust and selective relay coordination, this effect should be included in calculation of the optimal settings.

The number of coordination constraints in a large power system is remarkable. It is worth noting that the number is considerably increased when changes in network topology are taken into account. Therefore, the complexity of the problem is significantly increased, especially for the D&DOCRs coordination problem.

Constraints reduction in the DOCRs coordination problem has been investigated in previous papers. The feasibility of the optimization problem is increased by reducing the number of coordination constraints [15]. In [15], a method has been proposed for identifying non-valid constraints in the problem, in which changes on relay types and current settings have been suggested for removing these constraints. Furthermore, constraints reduction has been performed considering changes in network topology because of far-end line circuit breaker opening and transmission line outage. In [16], the problem has been solved using LP method considering definite time backup relaying, where a presolve analysis has been proposed to reduce the size and complexity of the LP problem. In [17], an algorithm has been introduced to reduce the effect of constraints on calculation of the optimal settings in which initial I_{set}s have been assumed for overcurrent relays, and then updated repeatedly until obtaining the optimal I_{set}s and *TMS*s. It is worth noting that the presented algorithms in [15–17] are dependent on the operating characteristics of overcurrent relays. In [18], an index has been presented for reducing the constraints by considering uncertainties in the fault location and network topology. Based on the index, it was proved that active or inactive constraints are recognizable for the International Electrotechnical Commission (IEC) operating characteristics.

When simultaneous coordination of distance and overcurrent relays is considered, a large number of coordination constraints are added to the DOCRs coordination constraints set, especially when different network topologies are taken into account. This increases the importance of constraints reduction. Previous constraints reduction algorithms have only aimed for DOCRs. Therefore, in this paper, at first, a new formulation is proposed for D&DOCRs coordination by taking different network topologies into account, and then, an efficient algorithm is developed for constraints reduction. Redundant constraints are identified using the proposed algorithm, without requiring the settings of distance and overcurrent relays, and the operating characteristics of overcurrent relays. Simulation results demonstrate significant reductions in constraints and the complexity of the problem, when the proposed algorithm is employed.

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2. DISTANCE AND DIRECTIONAL OVERCURRENT RELAYS COORDINATION PROBLEM

In the D&DOCRs coordination problem, the aim is to determine the distance and overcurrent relays settings such that the overall operating time of primary relays is minimized, as well as the relay coordination constraints are satisfied. In this paper, the following objective function is considered to calculate the optimal settings for D&DOCRs:

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

Different functions can be used for the operating characteristics of DOCRs, based on the IEC, IEEE, or AREVA standards. Generally, these characteristics are expressed as follows:

$$t = f(M) \times TMS \quad f(M) = \frac{K}{M^{\alpha} - 1} + \beta \quad M = \frac{I_{\text{fault}}}{I_{\text{set}}}. \tag{2}$$

I_{set} is the main reason of the objective function nonlinearity, which may be determined based on the engineering experiences or estimation (through an intelligent subproblem) within hybrid intelligent algorithms, which are used to solve the coordination problem. I_{set} of each overcurrent relay should be greater than the maximum load current and lower than the minimum fault current passing through the relay, by considering a security margin. From the view of engineering experiences, I_{set} is usually selected 1.1–1.3 times the maximum load current. For example, in [12], I_{set} of each overcurrent relay is selected as 1.2 times the maximum load current passing through the relay. In our study, maximum value among different load currents passing through the relay in direct direction due to network topology changes can be selected as maximum load current of the relay.

The D&DOCRs coordination problem should be solved by taking selectivity constraints and relay parameters constraints into account. These constraints are explained in the following.

2.1. *Selectivity constraints*

Selective and reliable operation of protection systems implies faster operation of primary relays than their backups, and the operation of backup relays in case of primary relays failure in clearing the faults [19]. The selectivity coordination constraints in the D&DOCRs coordination problem are divided into two groups: (1) selectivity constraints between overcurrent relays and (2) selectivity constraints between distance and overcurrent relays.

In order to obtain selectivity property between DOCRs, according to Figure 1, the following constraints should be considered in the coordination problem:

$$\begin{aligned} t_{\mathrm{b}}^{\mathrm{F}_1} - t_{\mathrm{p}}^{\mathrm{F}_1} &\geq CTI \\ t_{\mathrm{b}}^{\mathrm{F}_2} - t_{\mathrm{p}}^{\mathrm{F}_2} &\geq CTI \end{aligned} \tag{3}$$

CTI is typically in range of 0.2–0.5 s.

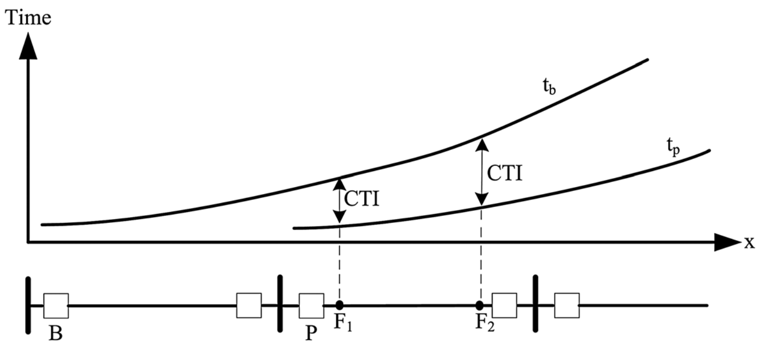

Figure 1. Selectivity illustration for overcurrent relays.

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Based on Figure 2, Equations (4) and (5) should be added to the DOCRs coordination problem in order to achieve a selective protection system. Equation (4) indicates selectivity property between backup overcurrent and primary distance relays. Furthermore, selectivity property between backup distance and primary overcurrent relays is defined by Equation (5):

$$t_{\mathrm{b}}^{\mathrm{F}_4} - T_{\mathrm{Z2p}} \geq CTI' \tag{4}$$

$$T_{\mathrm{Z2b}} - t_{\mathrm{p}}^{\mathrm{F}_3} \geq CTI' \tag{5}$$

CTI' is typically between 0.2 and 0.5 s, which may not be the same as CTI.

2.2. *Relay setting constraints*

Other constraints that should be considered in the coordination problem are related to the limits of time multiplier setting (TMS) and pickup current (I_{set}) of overcurrent relays. These constraints are defined as follows:

$$TMS_i^{\min} \leq TMS_i \leq TMS_i^{\max} \tag{6}$$

$$\max\left(I_{\mathrm{load}_i}^{\max}, I_{\mathrm{set}_i}^{\min}\right) \leq \mathrm{I}_{\mathrm{set}_i} \leq \min\left(I_{\mathrm{fault}_i}^{\min}, I_{\mathrm{set}_i}^{\max}\right). \tag{7}$$

2.3. *Coordination constraints considering changes in network topology*

Network impedance matrix and fault currents distribution vary because of changes in network topology. Therefore, miscoordination may occur and protection system may not be selective. Hence, changes in network topology should be considered in the D&DOCRs coordination problem in order to achieve a robust coordination. To achieve this goal, Equations (3)–(5) are modified into Equations (8)–(10), respectively:

$$\begin{array}{l} t_{\mathrm{b}s}^{\mathrm{F}_1} - t_{\mathrm{p}s}^{\mathrm{F}_1} \geq CTI \\ t_{\mathrm{b}s}^{\mathrm{F}_2} - t_{\mathrm{p}s}^{\mathrm{F}_2} \geq CTI \end{array} \qquad s \in S \tag{8}$$

$$t_{\mathrm{b}s}^{\mathrm{F}_4} - T_{\mathrm{Z2p}} \geq CTI' \qquad s \in S \tag{9}$$

$$T_{\mathrm{Z2b}} - t_{\mathrm{p}s}^{\mathrm{F}_3} \geq CTI' \qquad s \in S. \tag{10}$$

Based on these equations, in order to obtain robust coordination of distance and overcurrent relays, new coordination constraints, related to different network topologies, are added to the coordination constraints of the main network topology. Under this situation, the number of coordination constraints in the D&DOCRs coordination problem grows drastically, and the complexity of the problem is significantly increased.

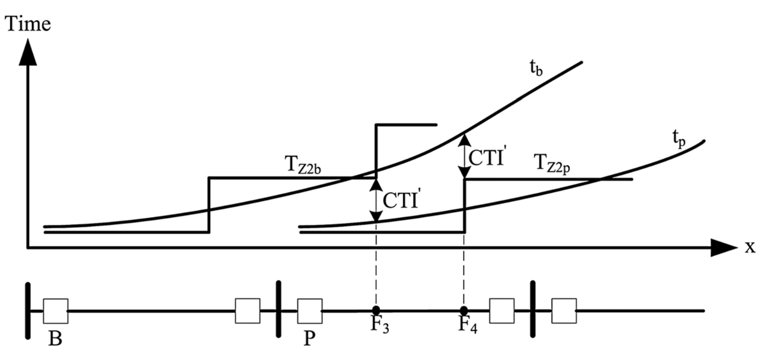

Figure 2. Selectivity illustration for distance and overcurrent relays.

3. PROPOSED METHOD FOR COORDINATION CONSTRAINTS REDUCTION

In this section, three algorithms are proposed and mathematically validated for redundant coordination constraints identification (RCCI) in the D&DOCRs coordination problem. It is worth noting that this identification is performed without solving the D&DOCRs coordination problem. Redundant coordination constraints are classified into two groups, including those that overlap with the other coordination constraints and those that are inactive constraints. Redundant coordination constraints do not affect the optimal settings and can be excluded from the constraints set.

3.1. Redundant coordination constraints identification between primary and backup overcurrent relays

The coordination constraints between primary overcurrent relay i and backup overcurrent relay j (COO) for two different network topologies (s and s') are defined as follows:

$$\begin{aligned}&COO_s = TMS_j\, f\left(M_{js}\right) - TMS_i\, f\left(M_{is}\right) - CTI\\&M_{is} = \frac{I_{\mathrm{fault}_{is}}}{I_{\mathrm{set}_i}} \qquad M_{js} = \frac{I_{\mathrm{fault}_{js}}}{I_{\mathrm{set}_j}} \qquad COO_s \geq 0\end{aligned} \tag{11}$$

$$\begin{aligned}&COO_{s'} = TMS_j\, f\left(M_{js'}\right) - TMS_i\, f\left(M_{is'}\right) - CTI\\&M_{is'} = \frac{I_{\mathrm{fault}_{is'}}}{I_{\mathrm{set}_i}} \qquad M_{js'} = \frac{I_{\mathrm{fault}_{js'}}}{I_{\mathrm{set}_j}} \qquad COO_{s'} \geq 0.\end{aligned} \tag{12}$$

The redundant coordination constraint identification index between primary and backup overcurrent relays ($RCCII_{oo}$) is defined as follows:

$$\begin{aligned}&RCCII_{OO} = \frac{\Delta I_i}{\Delta I_j}\\&\Delta I_i = \frac{M_{is'} - M_{is}}{M_{is}} = \frac{\dfrac{I_{\mathrm{fault}_{is'}}}{I_{\mathrm{set}_i}} - \dfrac{I_{\mathrm{fault}_{is}}}{I_{\mathrm{set}_i}}}{\dfrac{I_{\mathrm{fault}_{is}}}{I_{\mathrm{set}_i}}} = \frac{I_{\mathrm{fault}_{is'}} - I_{\mathrm{fault}_{is}}}{I_{\mathrm{fault}_{is}}}\\&\Delta I_j = \frac{M_{js'} - M_{js}}{M_{js}} = \frac{\dfrac{I_{\mathrm{fault}_{js'}}}{I_{\mathrm{set}_j}} - \dfrac{I_{\mathrm{fault}_{js}}}{I_{\mathrm{set}_j}}}{\dfrac{I_{\mathrm{fault}_{js}}}{I_{\mathrm{set}_j}}} = \frac{I_{\mathrm{fault}_{js'}} - I_{\mathrm{fault}_{js}}}{I_{\mathrm{fault}_{js}}}.\end{aligned} \tag{13}$$

Based on Equation (13), it can be seen that for two different network topologies, the $RCCII_{oo}$ is independent of the pickup current setting and only depends on the fault current passing through primary and backup overcurrent relays. In the following, three theorems are presented and proved to identify the redundant coordination constraints between primary and backup overcurrent relays based on the operating characteristic defined by IEC, ANSI/IEEE, and AREVA standards. It is worth noting that in [18], similar index has been proposed only for identification of redundant coordination constraints in the DOCRs coordination problem based on the operating characteristics presented by the IEC standard.

Theorem 1:For decreasing and convex function $f(x) = \frac{k}{x^{\alpha}-1} + \beta$, if $1 < a < b$ and $1 < a < c$, then:

$$\frac{a}{b} \leq \frac{c}{d} \qquad \Rightarrow \qquad \frac{f(a)}{f(b)} > \frac{f(c)}{f(d)}\,. \tag{14}$$

Before proving this theorem, the following lemma must be proved:

Lemma 1: If $1 < a < b,\ 1 < a < c$ and $\frac{a}{b} \leq \frac{c}{d}$ then $\frac{a-1}{b-1} < \frac{c-1}{d-1}$.

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Proof of Lemma (1) is explained as follows:

$$\begin{aligned} a<b, a<c \Rightarrow & \frac{(a-b)(a-c)}{a}>0 \quad \Rightarrow \quad \frac{a^2-(b+c)a+bc}{a}+1-1+bc-bc>0 \\ & \Rightarrow (1-b+bc-c)+\left(a-bc-1+\frac{bc}{a}\right)>0 \Rightarrow \quad (b-1)(c-1)>(a-1)\left(\frac{bc}{a}-1\right) \\ & \Rightarrow \frac{(b-1)(c-1)}{(a-1)}>\left(\frac{bc}{a}-1\right)>d-1 \quad \Rightarrow \quad \frac{a-1}{b-1}<\frac{c-1}{d-1} \end{aligned} \tag{15}$$

Proof of Theorem (1) regarding to this lemma is stated as follows:

$$\begin{aligned} & 1<a<b \text{ and } 1<a<c \text{ and } \frac{a}{b} \leq \frac{c}{d} \quad \Rightarrow \\ & 1<a^\alpha<b^\alpha \text{ and } 1<a^\alpha<c^\alpha \text{ and } \frac{a^\alpha}{b^\alpha} \leq \frac{c^\alpha}{d^\alpha} \end{aligned} \tag{16}$$

$$\begin{aligned} & \xrightarrow{(15) \text{ and } (16)} \Rightarrow \frac{a^\alpha-1}{b^\alpha-1}<\frac{c^\alpha-1}{d^\alpha-1} \Rightarrow \frac{\frac{k}{a^\alpha-1}}{\frac{k}{b^\alpha-1}}>\frac{\frac{k}{c^\alpha-1}}{\frac{k}{d^\alpha-1}} \\ & \Rightarrow \frac{\frac{k}{a^\alpha-1}+\beta}{\frac{k}{b^\alpha-1}}>\frac{\frac{k}{c^\alpha-1}+\beta}{\frac{k}{d^\alpha-1}} \quad \Rightarrow \quad \frac{f(a)}{f(b)}>\frac{f(c)}{f(d)}. \end{aligned} \tag{17}$$

Theorem 2: If, for coordination constraints (11) and (12), $RCCII_{OO} \leq 1,\ \Delta I_j<0,$ and $M_{js'}<M_{is'}$, then $COO_{s'}>COO_s$ and coordination constraint (12) can be removed from the coordination constraints set.

Theorem (2) states that if after any change in network topology, the fault currents passing through the primary and backup overcurrent relays are decreased and, moreover, decreasing in the absolute value of the fault current passing through the backup overcurrent relay is greater than that of the primary overcurrent relay, then the increase in the operating time of the backup relay would be greater than the increase in the operating time of the primary relay. Therefore, the difference between the operating times of the backup and primary relays is increased. So, by removing constraint (12) from the coordination constraints set, miscoordination does not occur. Proof of this theorem is as follows:

$$\begin{cases} RCCII_{OO} \leq 1 \\ \Delta I_j<0 \end{cases} \Rightarrow \Delta I_j \leq \Delta I_i \Rightarrow \frac{M_{js'}-M_{js}}{M_{js}} \leq \frac{M_{is'}-M_{is}}{M_{is}} \Rightarrow \frac{M_{js'}}{M_{is'}} \leq \frac{M_{js}}{M_{is}}. \tag{18}$$

Based on Theorem (1) and by replacing a, b, c, and d with $M_{js'}$, $M_{is'}$, M_{js}, and M_{is}, the following equation is resulted:

$$\frac{f(M_{js'})}{f(M_{is'})}>\frac{f(M_{js})}{f(M_{is})} \Rightarrow \frac{f(M_{is'})}{f(M_{js'})}<\frac{f(M_{is})}{f(M_{js})} \Rightarrow \frac{f(M_{is'})-f(M_{is})}{f(M_{js'})-f(M_{js})}<\frac{f(M_{is})}{f(M_{js})}. \tag{19}$$

Based on the coordination constraint (11), Equation (20) is obtained:

$$TMS_j\, f(M_{js})-TMS_i\, f(M_{is}) \geq CTI>0 \quad \Rightarrow \quad \frac{f(M_{is})}{f(M_{js})}<\frac{TMS_j}{TMS_i}. \tag{20}$$

Considering Equations (19) and (20):

$$\begin{aligned} \frac{f(M_{is'})-f(M_{is})}{f(M_{js'})-f(M_{js})}<\frac{TMS_j}{TMS_i} \quad & \Rightarrow \quad TMS_j\{f(M_{js'})-f(M_{js})\}>TMS_i\{f(M_{is'})-f(M_{is})\} \\ & \Rightarrow \quad TMS_j\, f(M_{js'})-TMS_i\, f(M_{is'})>TMS_j\, f(M_{js})-TMS_i\, f(M_{is}) \\ & \Rightarrow \quad COO_{s'}>COO_s. \end{aligned} \tag{21}$$

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Theorem 3: If, for coordination constraints (11) and (12), $RCCII_{OO} \leq 1,\ \Delta I_j > 0,$ and $M_{js'} < M_{is'}$, then $COO_s > COO_{s'}$ and coordination constraint (11) can be excluded from the coordination constraints set.

Based on Theorem (3), if after any change in network topology, the fault currents passing through the primary and backup overcurrent relays are increased and, in addition, increasing in the fault current passing through the backup overcurrent relay is smaller than that of the primary overcurrent relay, then the decrease in the operating time of the backup relay would be smaller than the decrease in the operating time of the primary relay. Therefore, the difference between the operating times of the backup and primary relays is increased. So, by removing constraint (11) from the coordination constraints set, miscoordination does not happen.

Proof: Proof of Theorem (3) is explained in the following:

$$\begin{cases} RCCII_{OO} \leq 1 \\ \Delta I_j > 0 \end{cases} \Rightarrow \quad \Delta I_i \leq \Delta I_j \Rightarrow \frac{M_{is'} - M_{is}}{M_{is}} \leq \frac{M_{js'} - M_{js}}{M_{js}} \Rightarrow \frac{M_{js}}{M_{is}} \leq \frac{M_{js'}}{M_{is'}}. \tag{22}$$

Based on Theorem (1) and by replacing a, b, c, and d with $M_{js},\ M_{is},\ M_{js'}$, and $M_{is'}$, respectively, the following equation is obtained:

$$\frac{f(M_{js})}{f(M_{is})} > \frac{f(M_{js'})}{f(M_{is'})} \Rightarrow \frac{f(M_{is})}{f(M_{js})} < \frac{f(M_{is'})}{f(M_{js'})} \Rightarrow \frac{f(M_{is}) - f(M_{is'})}{f(M_{js}) - f(M_{js'})} < \frac{f(M_{is'})}{f(M_{js'})}. \tag{23}$$

Based on the coordination constraint (12):

$$\mathrm{TMS}_j\, f(M_{js'}) - TMS_i\, f(M_{is'}) \geq CTI > 0 \Rightarrow \frac{f(M_{is'})}{f(M_{js'})} < \frac{TMS_j}{TMS_i}. \tag{24}$$

Equations (23) and (24) lead to the following equation:

$$\begin{aligned} &\frac{f(M_{is}) - f(M_{is'})}{f(M_{js}) - f(M_{js'})} < \frac{TMS_j}{TMS_i} \Rightarrow TMS_j\{f(M_{js}) - f(M_{js'})\} > TMS_i\{f(M_{is}) - f(M_{is'})\} \\ &\qquad \Rightarrow \mathrm{TMS}_j\, f(M_{js}) - \mathrm{TMS}_i\, f(M_{is}) > \mathrm{TMS}_j\, f(M_{js'}) - \mathrm{TMS}_i\, f(M_{is'}) \\ &\qquad \Rightarrow COO_s > COO_{s'}. \end{aligned} \tag{25}$$

3.2. *Redundant coordination constraints identification between primary distance and backup overcurrent relays*

It is assumed that the coordination constraints between primary distance relay i and backup overcurrent relay j (COD) for two different network topologies (s and s') are expressed using Equations (26) and (27):

$$COD_s = TMS_j\, f\left(M_{js}^{F_4}\right) - T_{Z2i} - CTI' \qquad M_{js}^{F_4} = \frac{I_{\mathrm{fault}_{js}}^{F_4}}{I_{\mathrm{set}_j}} \qquad COD_s \geq 0 \tag{26}$$

$$COD_{s'} = TMS_j\, f\left(M_{js'}^{F_4}\right) - T_{Z2i} - CTI' \qquad M_{js'}^{F_4} = \frac{I_{\mathrm{fault}_{js'}}^{F_4}}{I_{\mathrm{set}_j}} \qquad COD_{s'} \geq 0. \tag{27}$$

The redundant coordination constraint identification index between primary distance and backup overcurrent relays ($RCCII_{OD}$) is defined as follows:

$$RCCII_{OD} = \frac{M_{js'}^{F_4}}{M_{js}^{F_4}} = \frac{\frac{I_{\mathrm{fault}_{is'}}^{F_4}}{I_{\mathrm{set}_j}}}{\frac{I_{\mathrm{fault}_{is}}^{F_4}}{I_{\mathrm{set}_j}}} = \frac{I_{\mathrm{fault}_{is'}}^{F_4}}{I_{\mathrm{fault}_{is}}^{F_4}}. \tag{28}$$

Theorem 4: if $RCCII_{OD} \leq 1$, then $COD_{s'} \geq COD_s$ and coordination constraint (27) is redundant.

This theorem states that if fault current passing through the backup overcurrent relay decreases after a change in network topology, then the operating time of the relay will increase. Therefore, if

constraint (26) is satisfied, then constraint (27) will be satisfied, too. Thus, by removing constraint (27) from the coordination constraints set, miscoordination does not occur.
Proof: Proof of this theorem is stated as follows:

$$RCCII_{OD} \leq 1 \;\Rightarrow\; I^{F_4}_{\mathrm{fault}_{js'}} \leq I^{\mathrm{F}_4}_{\mathrm{fault}_{js}} \;\Rightarrow\; \frac{I^{\mathrm{F}_4}_{\mathrm{fault}_{js'}}}{I_{set_j}} \leq \frac{I^{\mathrm{F}_4}_{\mathrm{fault}_{js}}}{I_{set_j}} \;\Rightarrow\; M^{\mathrm{F}_4}_{js'} \leq M^{\mathrm{F}_4}_{js}$$
$$\Rightarrow f\left(M^{\mathrm{F}_4}_{js'}\right) \geq f\left(M^{\mathrm{F}_4}_{js}\right) \Rightarrow CDO_{s'} \geq CDO_s. \tag{29}$$

Based on Theorem (4), the maximum fault current passing through backup overcurrent relay *j*, for the fault at point F_4, among different network topologies, is selected for considering the coordination constraint between primary distance relay *i* and backup overcurrent relay *j*.

3.3. Redundant coordination constraints identification between primary overcurrent and backup distance relays

The coordination constraints between primary overcurrent relay *i* and backup distance relay *j* (*CDO*) for two different network topologies (*s* and *s*′) are defined as follows:

$$CDO_s = T_{Z2j} - TMS_i\, f\left(M^{\mathrm{F}_3}_{is}\right) - CTI' \quad M^{\mathrm{F}_3}_{is} = \frac{I^{\mathrm{F}_3}_{\mathrm{fault}_{is}}}{I_{\mathrm{set}_i}} \quad CDO_s \geq 0 \tag{30}$$

$$CDO_{s'} = T_{Z2j} - TMS_i\, f\left(M^{\mathrm{F}_3}_{is'}\right) - CTI' \quad M^{\mathrm{F}_3}_{is'} = \frac{I^{\mathrm{F}_3}_{\mathrm{fault}_{is'}}}{I_{\mathrm{set}_i}} \quad CDO_{s'} \geq 0\cdot \tag{31}$$

The redundant coordination constraint identification index between primary overcurrent and backup distance relays ($RCCII_{DO}$) is defined using Equation (32):

$$RCCII_{DO} = \frac{M^{\mathrm{F}_3}_{is'}}{M^{\mathrm{F}_3}_{is}} = \frac{\dfrac{I^{\mathrm{F}_3}_{\mathrm{fault}_{is'}}}{I_{\mathrm{set}_i}}}{\dfrac{I^{\mathrm{F}_3}_{\mathrm{fault}_{is}}}{I_{\mathrm{set}_i}}} = \frac{I^{\mathrm{F}_3}_{\mathrm{fault}_{is'}}}{I^{\mathrm{F}_3}_{\mathrm{fault}_{is}}}. \tag{32}$$

Theorem 5: if $RCCII_{DO} \leq 1$, then $CDO_s \geq CDO_{s'}$ and coordination constraint (30) is redundant.
According to this theorem, if fault current passing through the primary overcurrent relay decreases after a change in network topology, then the operating time of the relay will increase. Therefore, if constraint (31) is satisfied, then constraint (30) will be satisfied, too. Hence, miscoordination does not happen if constraint (30) is excluded from the coordination constraints set.
Proof: Proof of this theorem is as follows:

$$RCCII_{DO} \leq 1 \Rightarrow I^{\mathrm{F}_3}_{\mathrm{fault}_{is'}} \leq I^{\mathrm{F}_3}_{\mathrm{fault}_{is}} \;\Rightarrow\; \frac{I^{\mathrm{F}_3}_{\mathrm{fault}_{is'}}}{I_{set_i}} \leq \frac{I^{\mathrm{F}_3}_{\mathrm{fault}_{is}}}{I_{set_i}} \;\Rightarrow\; M^{\mathrm{F}_3}_{is'} \leq M^{\mathrm{F}_3}_{is}$$
$$\Rightarrow f\left(M^{\mathrm{F}_3}_{is}\right) \leq f\left(M^{\mathrm{F}_3}_{is'}\right) \;\Rightarrow\; CDO_s \geq CDO_{s'}. \tag{33}$$

Based on Theorem (5), the minimum fault current passing through primary overcurrent relay *i*, for the fault at point F_3, among different network topologies, is selected to account for the coordination constraint between primary overcurrent relay *i* and backup distance relay *j*. In selection of the minimum fault current, it should be noted that this current must be greater than the pickup current of overcurrent relay *i*, that is:

$$I^{\mathrm{F}_3}_{\mathrm{fault}_{is}} \geq I_{\mathrm{set}_i}. \tag{34}$$

To investigate this condition, pickup current of each overcurrent relay should be determined. This can be carried out using several methods such as engineering experiences or by solving the coordination problem using hybrid LP and intelligent algorithms, before starting the LP subproblem. However, in order to make the proposed constraints reduction algorithm independent of pickup current settings, inequality (35) can be checked instead of Equation (34) for the selection of the minimum

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valid fault current passing through overcurrent relay i based on the relay setting limits presented in Equation (7):

$$I_{\mathrm{fault}_{is}}^{\mathrm{F}_3} \geq \min\left(I_{\mathrm{fault}_i}^{\min}, I_{\mathrm{set}_i}^{\max}\right). \tag{35}$$

Flowchart of the proposed algorithm for the D&DOCRS coordination constraints reduction, considering changes in network topology is illustrated in Figure 3. The algorithm can be explained in the following five main steps:

Step 1. Fault currents passing through primary overcurrent relays at point F_3, backup overcurrent relays at point F_4, and primary and backup overcurrent relays at near-end faults are calculated for the main network topology.

Step 2. Fault currents passing through primary overcurrent relays at point F_3, backup overcurrent relays at point F_4, and primary and backup overcurrent relays at near-end fault are calculated after changing the network topology.

Step 3. Coordination constraints reduction is performed as follows:

- For primary and backup overcurrent relays:

  (1) Based on Theorem (2), if $RCCII_{OO} \leq 1, \Delta I_j < 0,$ and $M_{js'} < M_{is'}$, then the coordination constraint related to the new network topology is removed from the constraints

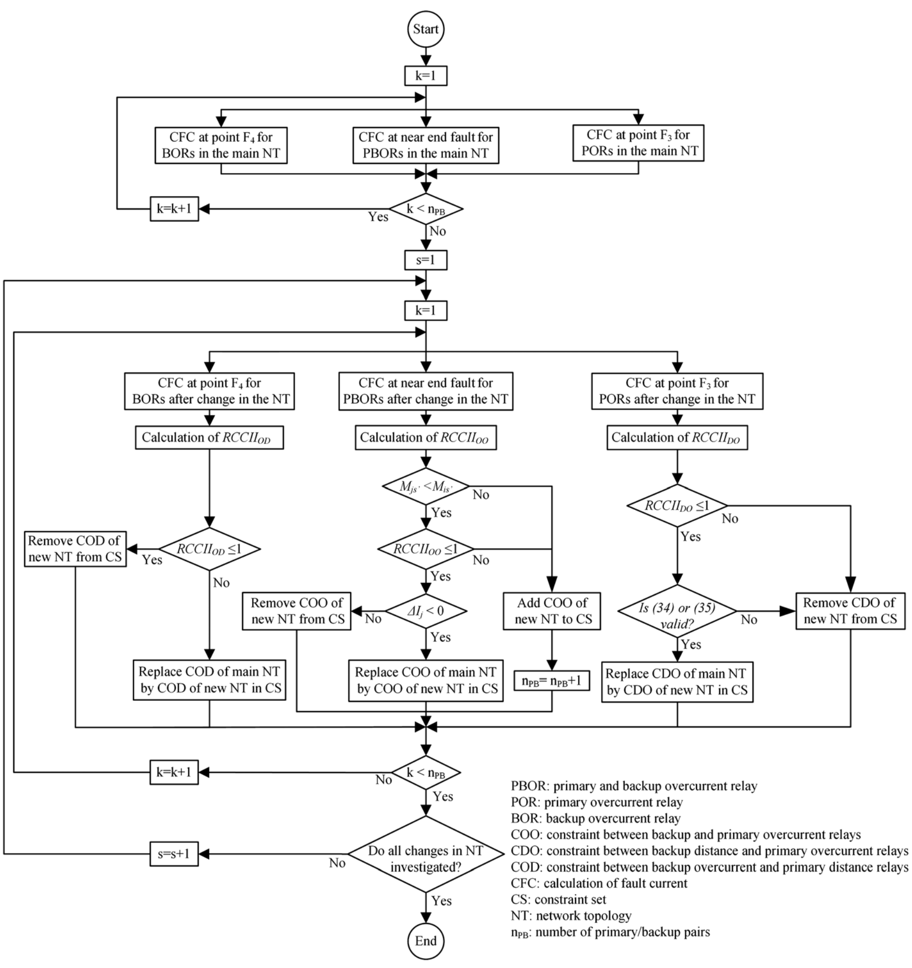

Figure 3. Flowchart of the proposed algorithm for D&DOCRs coordination constraints reduction.

set. Therefore, the fault currents passing through primary and backup overcurrent relays, related to the new network topology, are eliminated.

(2) Based on Theorem (3), if $RCCII_{OO} \leq 1$, $\Delta I_j > 0$, and $M_{js'} < M_{is'}$, then the coordination constraint related to the main network topology is replaced by that related to the new network topology. Therefore, the fault currents passing through primary and backup overcurrent relays, related to the new network topology, are employed instead of those of the main network topology.

(3) If $RCCII_{oo} > 1$, then the coordination constraint for the new network topology is added to the coordination constraints set.

- For primary distance and backup overcurrent relays:

(1) Based on Theorem (4), if $RCCII_{OD} \leq 1$, then the coordination constraint related to the new network topology is removed from the constraints set. Therefore, the fault current passing through backup overcurrent relay in the new network topology is eliminated.

(2) If $RCCII_{OD} > 1$, then the coordination constraint of the main network topology is replaced by the coordination constraint related to the new network topology. Therefore, the fault current passing through the backup overcurrent relay in the new network topology is considered, instead of that in the main network topology.

- For primary overcurrent and backup distance relays:

(1) Based on Theorem (5), if $RCCII_{DO} \leq 1$ and conditions (34) or (35) are met, then the coordination constraint of the main network topology is excluded from the constraints set. Therefore, the fault current passing through the primary overcurrent relay in the new network topology is considered instead of that in the main network topology.

(2) If $RCCII_{DO} > 1$ or any of conditions (34) or (35) are not satisfied, then the coordination constraint related to the new network topology is removed from the constraints set. Therefore, the fault current passing through the backup overcurrent relay related to the new network topology is eliminated.

Step 4. Step 3 is repeated for all primary and backup relay pairs.

Step 5. Steps 2, 3, and 4 are repeated until all different network topologies are investigated and redundant coordination constraints are identified and excluded from the coordination constraints set.

4. SIMULATION RESULTS

In order to evaluate the proposed algorithm for the D&DOCRs coordination constraints reduction, the algorithm is tested on two case studies, including an 8-bus and the IEEE 14-bus test systems. In this paper, single-line outages (both ends of line are opened) are considered as the source of change in network topology. Furthermore, fault currents for relay coordination are calculated at the near-end fault of the relay, end of the first zone of the primary distance relays, that is, 80% of the transmission line length, and end of the second zone of the backup distance relays, that is, 50% of the shortest line protected by the primary distance relays. In both cases, that is, with and without constraints reduction, the *TMS* for each DOCR is assumed as a continuous variable between 0.05 and 1.1. After reduction of the coordination constraints, linear programming is used to solve the coordination problem. Without loss of generality, very inverse operating characteristic ($K = 13.5$, $\alpha = 1$, and $\beta = 0$) based on the IEC standard is considered as the operating characteristic of the overcurrent relays.

4.1. Test system 1

The 8-bus test system, shown in Figure 4, is a 150 kV power system composed of seven transmission lines, two generators, and two transformers. The transmission lines are protected by 14 distance relays

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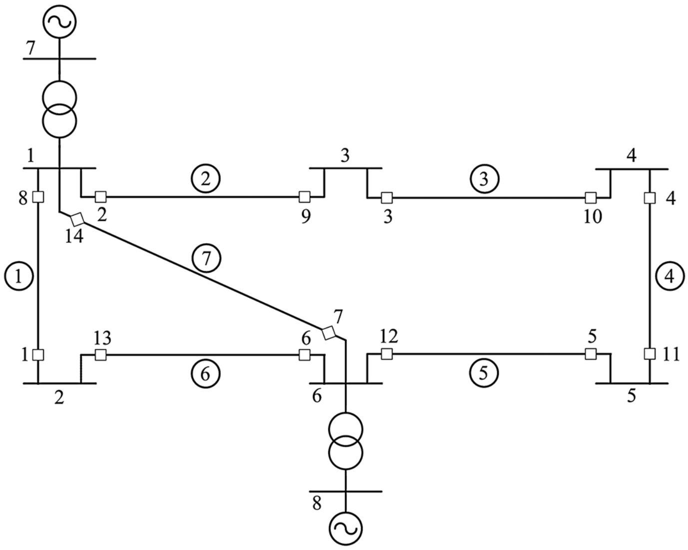

Figure 4. Single-line diagram of the 8-bus test system.

Table I. Fault currents passing through the primary and backup overcurrent relay at different locations in main network topology.

Relay no.		Fault at point F_1		Fault at point F_3	Fault at point F_4
PR	BR	PR	BR	PR	BR
1	6	2703	2703	1756	1200
2	1	5390	812	4198	391
2	7	5390	1540	4198	742
3	2	3347	3347	2747	2436
4	3	2243	2243	1792	1533
5	4	1361	1361	918	628
6	5	4995	416	3697	91
6	14	4995	1540	3697	336
7	5	4267	416	2927	244
7	13	4267	812	2925	475
8	7	4995	1540	3577	219
8	9	4995	416	3576	59
9	10	1453	1453	967	649
10	11	2345	2345	1885	1625
11	12	3495	3495	2867	2544
12	13	5391	812	4297	425
12	14	5391	1540	4299	806
13	8	2507	2507	1665	1162
14	1	4267	812	2796	475
14	9	4267	416	2796	244

PR, primary relay; BR, backup relay.

and 14 DOCRs. The test system data and pickup current of overcurrent relays can be found in [20]. Table I presents the fault currents in the selected locations for relay coordination in the main network topology. Fault current distribution and magnitude are changed by changing the network topology. For example, fault currents at the same location in network topology after the outage of line 7 are shown in Table II.

In this system, there are 20 pairs of primary and backup relays. Therefore, in the main network topology, there are 60 coordination constraints for the D&DOCRs coordination problem (20 *COO*s, 20 *COD*s, and 20 *CDO*s). By considering different network topologies due to single-line outages, this number is increased to 360 (120 *COO*s, 120 *COD*s, and 120 *CDO*s). After applying the proposed coordination constraints reduction algorithm, the number of coordination constraints is reduced to

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Table II. Fault currents passing through the primary and backup overcurrent relay at different locations in network topology after outage of line 7.

Relay no.		Fault at point F_1		Fault at point F_3	Fault at point F_4
PR	BR	PR	BR	PR	BR
1	6	2660	2660	2133	1839
2	1	4684	1646	3802	821
3	2	3140	3140	2661	2409
4	3	2252	2252	1887	1681
5	4	1545	1545	1206	993
6	5	3883	844	3210	193
8	9	3883	844	3144	126
9	10	1618	1618	1243	1009
10	11	2335	2335	1963	1754
11	12	3257	3257	2757	2497
12	13	4684	1646	3877	890
13	8	2550	2550	2083	1820

71 (31 *COO*s, 20 *COD*s, and 20 *CDO*s). This reduction is equivalent to 80.28%, which is considerable. Three out of 31 coordination constraints between primary and backup overcurrent relays are related to the main network topology. Furthermore, 17 coordination constraints of the main topology are replaced by new constraints from other topologies, and also, 2 and 9 constraints are added to the constraints set because of $RCCII_{oo} > 1$ and $M_{js'} \geq M_{is'}$, respectively. Moreover, all coordination constraints between primary/backup distance and primary/backup overcurrent relays of the main topology are replaced by new constraints from other topologies.

The D&DOCRs coordination problem is solved using LP method in both cases, that is, with and without constraints reduction. The optimal settings of the D&DOCRs are presented in Table III. Results of this table show that the optimal settings are identical in both cases, indicating satisfactory performance of the proposed redundant constraints reduction algorithm. Based on the presented results in Table III, it can be seen that high values are obtained for T_{Z2}s by satisfying all coordination constraints. It is worth noting that if the operation times of the second zones of the distance relays are

Table III. The optimal settings of the D&DOCRs for the 8-bus test system by considering changes in network topology.

		Without constraints reduction		With constraints reduction	
Relay no.	I_{set}	TMS	T_{Z2}	TMS	T_{Z2}
1	120	1.0330	1.3347	1.0330	1.3347
2	480	0.5817	1.5169	0.5817	1.5169
3	240	0.9840	0.7302	0.9840	0.7302
4	360	0.1562	0.9242	0.1562	0.9242
5	240	0.1515	0.9995	0.1515	0.9995
6	480	0.3219	1.2229	0.3219	1.2229
7	240	0.6487	1.2530	0.6487	1.2530
8	360	0.4512	1.2770	0.4512	1.2770
9	240	0.1533	1.0120	0.1533	1.0120
10	360	0.1618	0.8833	0.1618	0.8833
11	240	0.9666	0.7158	0.9666	0.7158
12	480	0.5777	1.4443	0.5777	1.4443
13	120	1.0272	1.3020	1.0272	1.3020
14	240	0.6403	1.2194	0.6403	1.2194
Optimal objective function		24.3177		24.3177	
Sum of the DOCRs operating time		8.4825		8.4825	
Average T_{Z2}		1.1311		1.1311	
Number of constraints		**360**		**71**	

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limited to the typical range of 0.3–0.6 s, the problem has no feasible solution for the 8-bus test system. In some previous studies, the effect of T_{Z2} value on the feasibility of the problem has been investigated on a fixed network topology. In [9], it has been reported that by considering 0.6 s for T_{Z2}, the solution is not feasible, whereas the solution is achievable, if T_{Z2} is assumed to be 0.8 s. Furthermore, high values for T_{Z2}s are obtained in other studies, for example, 1 s in [10], 0.98 s in [11], 1.13 s in [12], and 0.9 s in [13], all of which were trying to satisfy the coordination constraints for a fixed network topology. Based on these results, it can be seen that in order to obtain feasible solution the T_{Z2}s were out of the typical range. Furthermore, values of T_{Z2}s depend on network topology, as in the following, it is shown that these values in the IEEE 14-bus test system is more rational than those in the 8-bus test system.

4.2. Test system 2

The IEEE 14-bus test system serves as another test system in this study to evaluate the performance of the proposed constraints reduction algorithm. The single-line diagram of this system

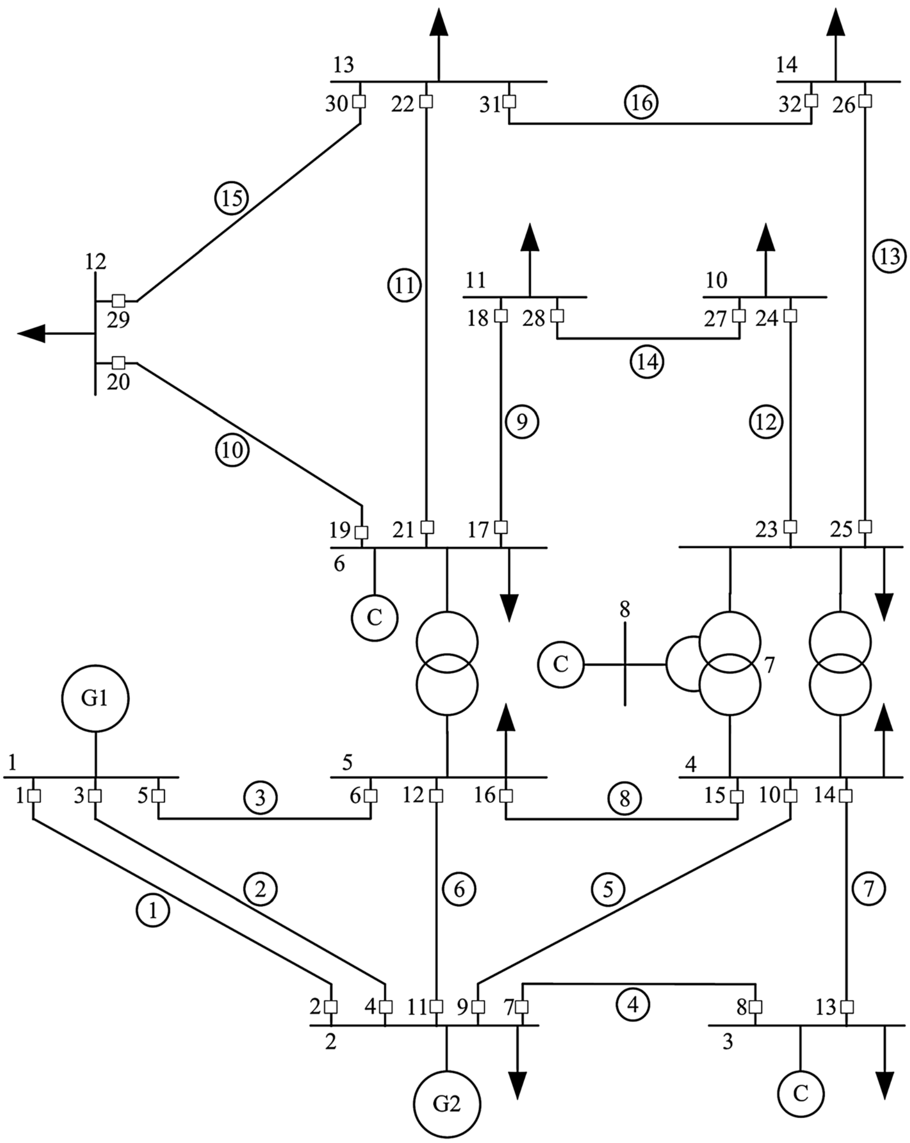

Figure 5. Single-line diagram of the IEEE 14-bus test system.

is shown in Figure 5. IEEE 14-bus test system is made of 5 synchronous machines including 2 synchronous generators and 3 synchronous compensators, 3 transformers, and 16 transmission lines. It is assumed that the lines are protected by 32 distance relays, as well as 32 DOCRs. Detailed information about this test system is given in [21]. Pickup current settings of DOCRs are selected based on [22].

The number of primary and backup relay pairs is 62 for this case study, leading to 186 coordination constraints for the D&DOCRs coordination problem (62 *COO*s, 62 *COD*s, and 62 *CDO*s) in the main network topology. This number is increased to 2790 (930 *COO*s, 930 *COD*s, and 930 *CDO*s) if coordination constraints of different network topologies are taken into account. By employing the proposed constraints reduction algorithm, the number of coordination constraints is reduced to 234 (110 *COO*s, 62 *COD*s, and 62 *CDO*s), equivalent to the remarkable reduction of 91.61%. Four out of 110 coordination constraints between primary and backup overcurrent relays are related to the main network topology, and also, 60 coordination constraints of the main topology are replaced by new constraints from other topologies. Moreover, 11 and 35 constraints are added to the constraints set because of $RCCII_{oo} > 1$ and $M_{js'} \geq M_{is'}$, respectively. Furthermore, all coordination constraints between

Table IV. The optimal settings of the D&DOCRs for the IEEE 14-bus test system by considering changes in network topology.

		Without constraints reduction		With constraints reduction	
Relay no.	I_{set}	TMS	T_{Z2}	TMS	T_{Z2}
1	450	0.0500	0.5377	0.0500	0.5377
2	500	0.0730	0.5058	0.0730	0.5058
3	450	0.0500	0.5377	0.0500	0.5377
4	500	0.0730	0.5058	0.0730	0.5058
5	200	0.2117	0.8784	0.2117	0.8784
6	400	0.0500	0.4590	0.0500	0.4590
7	900	0.0500	0.5702	0.0500	0.5702
8	400	0.0500	0.4599	0.0500	0.4599
9	600	0.0500	0.7499	0.0500	0.7499
10	500	0.0500	0.5355	0.0500	0.5355
11	600	0.0500	0.7757	0.0500	0.7757
12	300	0.0514	0.5377	0.0514	0.5377
13	100	0.4939	0.6813	0.4939	0.6813
14	500	0.0500	0.4009	0.0500	0.4009
15	800	0.0500	0.3979	0.0500	0.3979
16	800	0.0500	0.5342	0.0500	0.5342
17	500	0.3572	0.7181	0.3572	0.7181
18	300	0.1723	0.5466	0.1723	0.5466
19	800	0.1944	0.9730	0.1944	0.9730
20	100	0.1847	0.5466	0.1847	0.5466
21	700	0.2561	0.5275	0.2561	0.5275
22	140	0.2011	0.5810	0.2011	0.5810
23	900	0.1882	0.5672	0.1882	0.5672
24	300	0.1912	0.5870	0.1912	0.5870
25	400	0.3031	0.7173	0.3031	0.7173
26	250	0.2180	0.6249	0.2180	0.6249
27	400	0.2456	0.5431	0.2456	0.5431
28	600	0.1806	0.5796	0.1806	0.5796
29	350	0.3413	0.8524	0.3413	0.8524
30	300	0.1753	0.4449	0.1753	0.4449
31	400	0.2160	0.9585	0.2160	0.9585
32	300	0.2552	0.6849	0.2552	0.6849
Optimal objective function		25.3345		25.3345	
Sum of the DOCRs operating time		5.8143		5.8143	
Average T_{Z2}		0.6100		0.6100	
Number of constraints		**2790**		**234**	

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primary/backup distance and primary/backup overcurrent relays of the main topology are replaced by new constraints from other topologies.

Table IV presents the optimal settings of the D&DOCRs. The coordination problem is solved using the LP method in both cases, that is, with and without constrains reduction. Based on the presented results in this table, similar optimal settings are obtained in both cases.

5. CONCLUSION

In this paper, a novel algorithm has been proposed for identification of redundant coordination constraints in distance and overcurrent relays coordination problem by considering changes in network topology. In this study, it is assumed that single-line outages have led to changes in network topology. It is shown that the proposed constraints reduction algorithm is independent of the settings of D&DOCRs and operating characteristics of overcurrent relays, with operating characteristics based on the IEC, IEEE/ANSS, or AREVA standards. In addition, the proposed constraints reduction algorithm does not need the coordination problem to be solved. Based on the presented results, the coordination constraints are reduced up to 80.28% and 91.61% for the 8-bus and IEEE 14-bus test systems, respectively, when different network topologies are taken into account in the coordination problem. The simulation results demonstrate that the proposed method is successful in the coordination constraints reduction and can be used in large power systems in order to achieve robust and selective relay coordination.

6. LIST OF SYMBOLS AND ABBREVIATIONS

6.1. Abbreviations

D&DOCRs	distance and directional overcurrent relays
DOCRs	directional overcurrent relays
PR	primary relay
BR	backup relay
TMS	time multiplier settings
LP	linear programming
GA	genetic algorithm
PSO	particle swarm optimization
RCCI	redundant coordination constraints identification

6.2. Symbols

I_{set}	pickup current setting of overcurrent relays
$I_{\text{set}_i}^{\min}$ and $I_{\text{set}_i}^{\max}$	minimum and maximum available pickup current of the ith overcurrent relay, respectively
$I_{\text{load}_i}^{\max}$	maximum load current passing through of the ith overcurrent relay
I_{fault}	fault current passing through the relay
$I_{\text{fault}_i}^{\min}$	minimum fault current passing through of the ith overcurrent relay
$I_{\text{fault}_{is}}$ and $I_{\text{fault}_{is'}}$	fault current passing through primary overcurrent relay when the fault occurs in the transmission line of primary relay in network topologies s and s', respectively
$I_{\text{fault}_{js}}$ and $I_{\text{fault}_{js'}}$	fault current passing through backup overcurrent relay when the fault occurs in the transmission line of primary relay in network topologies s and s', respectively
$I_{\text{fault}_{is}}^{\text{F}_3}$ and $I_{\text{fault}_{is'}}^{\text{F}_3}$	fault currents passing through primary overcurrent relay i for the fault at point F_3 in network topologies s and s', respectively
$I_{\text{fault}_{js}}^{\text{F}_4}$ and $I_{\text{fault}_{js'}}^{\text{F}_4}$	fault currents passing through backup overcurrent relay j for the fault at point F_4 in network topologies s and s', respectively
M	ratio of the fault current passing through the relay to its pickup current

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t_i	operating time of the ith overcurrent relay for the near-end fault
$t_{\mathrm{p}}^{\mathrm{F}_1}$ and $t_{\mathrm{b}}^{\mathrm{F}_1}$	operating times of primary and backup overcurrent relays for the near-end fault (point F_1), respectively
$t_{\mathrm{p}}^{\mathrm{F}_2}$ and $t_{\mathrm{b}}^{\mathrm{F}_2}$	operating times of primary and backup overcurrent relays for the far-end fault (point F_2), respectively
$t_{\mathrm{b}}^{\mathrm{F}_4}$	operating time of backup overcurrent relays for the faults at the end of the first zone of primary distance relays (point F_4)
$t_{\mathrm{p}}^{\mathrm{F}_3}$	operating time of primary overcurrent relays for the fault at the end of the second zone of backup distance relays (point F_3)
T_{Z2}	operating time of the second zone
$T_{\mathrm{Z2}j}$	operating time of the second zone of the jth distance relay
T_{Z2p} and T_{Z2b}	operating times of the second zone of primary distance and backup relays, respectively
$\mathrm{TMS}_i^{\min}$ and $\mathrm{TMS}_i^{\max}$	minimum and maximum available time multiplier settings of the ith overcurrent relay, respectively
CTI	coordination time interval between primary and backup overcurrent relays
CTI'	coordination time interval between distance and overcurrent relays
S	set of network topologies
COO_s and $COO_{s'}$	coordination constraint between primary and backup overcurrent relays in network topologies s and s', respectively
COO_s and $COD_{s'}$	coordination constraint between primary distance and backup overcurrent relays in network topologies s and s', respectively
CDO_s and CDO_s'	coordination constraint between primary overcurrent and backup distance relays in network topologies s and s', respectively
$RCCII_{oo}$	redundant coordination constraint identification index between primary and backup overcurrent relays
$RCCII_{OD}$	redundant coordination constraint identification index between primary distance and backup overcurrent relays
$RCCII_{DO}$	redundant coordination constraint identification index between primary overcurrent and backup distance relays
n	number of directional overcurrent relays
m	number of distance relays
K, α, and β	constant values that are selected based on the type of operating characteristics of DOCR

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