IET Generation, Transmission & Distribution

Research Article

Dual-setting characteristic for directional overcurrent relays considering multiple fault locations

ISSN 1751-8687
Received on 10th July 2014
Revised on 20th January 2015
Accepted on 11th February 2015
doi: 10.1049/iet-gtd.2014.0683
www.ietdl.org

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Abstract: Optimal relay settings are determined where coordination constraints are modelled considering only either one fault location (near end or midpoint) or two fault locations (near and far end) on a feeder. This study, first, investigates whether considering one or two fault locations is sufficient to guarantee proper coordination for faults at all other locations on a feeder. The results show that violations, in the coordination constraints, can occur at various points along the feeder if the relays are coordinated considering one or two fault locations. In addition, considering multiple fault locations while determining the optimal relay setting can avoid such problem but on the expense of the overall relay tripping time. Thus, a dual-setting characteristic for directional overcurrent relays (DOCRs) is proposed instead of the conventional inverse time-current characteristic. The study is conducted on the power transmission system of IEEE 24-bus and the power distribution system of IEEE 14-bus. The proposed characteristic achieves notable reduction in total DOCRs operating time over the conventional characteristic for both test systems while achieving proper coordination across a broader range of possible fault locations.

1 Introduction

Directional overcurrent relays (DOCRs) are protective relays usually utilised in interconnected power networks because of the flow of bi-directional fault currents. In power transmission systems, these relays are considered a reliable and low cost alternative compared with distance or pilot relays [1, 2]. Moreover, DOCRs are used for the protection of meshed distribution systems with possible integration of distributed generation (DG) units [3–8]. One of the main challenges while designing protection schemes is to ensure accurate coordination of all relays in a power system [9]. To assure proper protection coordination, a set of primary relays are utilised to quickly isolate faulted sections with backup relays designed to operate within a sufficient coordination margin, in case a primary relay fails to operate [10].

Recently, in the literature, optimisation techniques have been commonly used to solve the protection coordination problem of interconnected systems [3–5, 11–19]. In such studies, the DOCRs tripping times are governed by an inverse time-current characteristic. The main objective is to minimise the tripping times of all primary and backup relays subject to protection coordination, relay setting and relay operating time constraints. However, the results are affected by the coordination constraint sets considered which are dependent on the fault location. In [4, 5, 11], DOCR coordination is based only on faults implemented midway along each line in a power network. On the other hand, studies performed, by authors in [12–16], considered DOCR coordination based on near-end faults only whereas, authors in [17–20], considered near-end and far-end faults for protection coordination. According to Ezzeddine *et al.*, [18] and Birla *et al.*, [20], solving the protection coordination problem based on only near-end faults results in violation of many of the coordination constraints when tested for far-end faults. The number of coordination constraint violation decreases by solving the problem considering both near-end and far-end faults. To eliminate all violations, Ezzeddine *et al.*, [18] proposed a method that selects the pickup currents as a function of selectivity constraints and accordingly predicting the time dial settings of each DOCR. On the other hand, Birla *et al.*, [20] suggests solving the problem by changing the objective function to the sum of violations of all valid constraints. Although the proposed methods, in [18, 20], can eliminate the violations of constraints, the optimal overall tripping time experiences a notable increase. Moreover, both studies considered only two candidate fault locations for coordination and thus the coordination problem solutions might not be valid for other fault locations.

In this paper, several coordination constraints sets are investigated such as coordination based on midway, near-end, near-end/far-end, near-end/midway/far-end and every 10% of the line fault locations along each line in a power interconnected system. In this study the protection coordination problem is formulated as a constrained non-linear programming (NLP) problem to determine the optimal relay settings for a system. The study is tested on the power transmission system of IEEE 24-bus and the power distribution system of the IEEE 14-bus standard test system with synchronous generator-based DG units. This paper proposes a dual-setting relay characteristic that can achieve notable reduction in total DOCRs operating time over the conventional characteristic for both test systems while achieving proper coordination across a broader range of possible fault locations. A comparative study is presented that highlights the advantages of the proposed characteristic over the conventional inverse time-current characteristic.

2 Protection coordination problem

The DOCR operation time is determined by an inverse function of the fault current passing through it. Depending on the standard followed by the relay manufacturer and type of the DOCR used, the characteristic equation governing the operation time differs. In this paper, it is assumed that identical DOCRs are used that follow the IEC255-3 standard characteristic equation represented by [21]

$$t_{ij} = \mathrm{TDS}_i \frac{A}{(I_{\mathrm{sc}ij}/I_{\mathrm{p}i})^B - 1} \tag{1}$$

where i is the relay identifier and j is the fault location identifier. t_{ij} is the tripping time (in seconds) of relay i for a fault at location j. $I_{\mathrm{sc}ij}$ is the short circuit current measured at the secondary winding of the current transformer of relay i for a fault at location j. The pickup current I_{p_i} is the threshold current above which the relay i will operate. TDS_i is the time dial setting of relay i used as a tuning parameter. Constants A and B are set to 0.14 and 0.02, respectively, based on the IEC standard normal inverse characteristic expression. The short circuit current seen by each DOCR depends on the location of the fault along the lines protected. Fig. 1 shows a fault node denoted by $F_{\%}$ where the subscript % refers to the fault location as a percentage of the line length measured from the low numbered bus. For example, $F_{30\%}$ would indicate that a fault occurred at a distance of 30% of the line length from Bus 2.

To find the optimal I_{p} and TDS settings of each DOCR in a power system, the protection coordination optimisation (PCO) model is developed for each system under study [6]. The objective is to minimise the sum of primary and backup DOCRs operating time (T) while maintaining the conditions of protection coordination. Hence, the objective function is given as

$$\text{Minimise} \quad T = \sum_{j=1}^{M} \sum_{i=1}^{N} \left(t_{ij}^{p} + \sum_{x=1}^{X} t_{ij}^{b_x} \right) \tag{2}$$

where N is the total number of relays and M is the total number of fault locations investigated. The superscript p represents primary relays, whereas b_x represents backup relay x with X being the number of backup relays for each primary relay. The variables t_{ij}^{p} and $t_{ij}^{b_x}$ refer to the primary and backup relay i operating time for a fault location j, respectively.

The PCO model considers three sets of constraints that must be satisfied so that optimal feasible solution is achieved. The first set of constraints is imposed on the relay settings. The TDS value of each DOCR is constrained by lower and upper limits ($\mathrm{TDS}_{i-\min}$ and $\mathrm{TDS}_{i-\max}$), which are set to 0.05 and 1, respectively, as shown in (3). Similarly, the second setting I_{p} for each DOCR is limited between $I_{\mathrm{p}_{i-\min}}$ and $I_{\mathrm{p}_{i-\max}}$ as indicated in (4). $I_{\mathrm{p}_{i-\min}}$ for each DOCR is selected to be higher than the rated load current of the line that it protects so as to ensure that each DOCR will trip only if a fault occurs. For simplicity, the condition of taking discrete I_{p} values is relaxed and accordingly the values are continuous [4, 5]

$$\mathrm{TDS}_{i-\min} \leqslant \mathrm{TDS}_i \leqslant \mathrm{TDS}_{i-\max} \quad \forall i \tag{3}$$

$$I_{\mathrm{p}_{i-\min}} \leqslant I_{\mathrm{p}_i} \leqslant I_{\mathrm{p}_{i-\max}} \quad \forall i \tag{4}$$

The second set of constraints limit each primary DOCR operating time by a lower limit, which is set to 20 ms because of the fact that the typical fastest operation time of the DOCR falls within one cycle [22]. This set of constraints can be expressed as follows

$$t_{ij}^{p}, t_{ij}^{b_x} \geqslant t_{ij-\min} \quad \forall i, j, x \tag{5}$$

Finally, coordination constraints must be satisfied by maintaining a minimum gap in time between the operation of primary and backup DOCRs, known as the coordination time interval (CTI). In this paper, CTI is set as 300 ms. Such constraints can be defined as

$$t_j^{b_x} - t_j^{p} \geqslant \mathrm{CTI} \quad \forall j, x \tag{6}$$

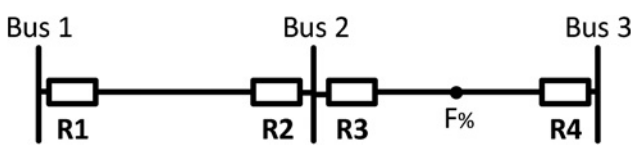

Fig. 1 *Diagram showing fault location as percentage of a line*

Table 1 Defining several coordination constraints sets

Sets	Fault locations
1	midway only
2	near-end only
3	near-end and far-end
4	near-end and midway and far-end
5	near-end and every 10% and far-end

The number of coordination constraints will depend on the number of fault locations considered per line. Table 1 summarises the different coordination constraints sets that are considered in this study. The coordination constraints for cases when the short circuit current seen by a DOCR is less than its corresponding $I_{\mathrm{p}_{i-\min}}$ are not included in the PCO model [20, 23]. In such situation, the DOCR will not operate and thus excluded from the summation of overall operating time T in the objective function.

3 System and solver details

This section provides a detailed description of the two systems under study. The first system is the IEEE 24-bus, whereas the second is the distribution system section of the IEEE 14-bus test system. These systems were chosen to test the five coordination constraints sets on both transmission and distribution interconnected systems. Finally, a brief explanation of the solver and testing techniques is provided in the last section.

3.1 Test systems description

The power transmission system selected in this study is the IEEE 24-bus [24, 25]. The single line diagram of this system is shown in Fig. 2. The 24 buses of this system are connected by 34 lines that are at two voltages levels, 138 and 230 kV. Five 230 kV/138 kV transformer stations located at buses 11, 12 and 24 are used to tie the 230 kV (top part) with the 138 kV system (see Fig. 2). A total of 32 generation units with various ratings are located at 10 buses as shown in Table 2. Full system dynamic data including the reactance of each generator with its step-up transformer is provided in [25, 26].

The system is equipped with 68 DOCRs. Additional 34 nodes are introduced one at each line in the system ($F25-F58$) at which bolted three-phase fault is conducted. Each node is duplicated at various locations on the same line based on the coordination constraints set or testing mechanism simulated. For example, if coordination constraints set 4 is simulated, node $F1$ will be duplicated three times at near end, midpoint and far end of line Bus1–Bus2. Similarly, the other fault nodes will follow the same pattern for that specific coordination constraints set. Accordingly, the number of fault locations simulated in this example is triple the number of faults if sets 1 or 2 were applied. However, regardless of the coordination constraints set simulated, for fault nodes $F30$, $F31$, $F32$, $F33$ and $F34$, locations are always near-end and far-end only. This is because of the presence of the transformer stations.

For each fault location, two primary DOCRs are assigned, one from each side in which each is backed up by other DOCRs. Depending on the fault location, the number of backup DOCR for each primary DOCR varies which can reach up to four backups per primary. This large number is mainly because of the meshed nature of the system. For instance, if a fault occurs at node $F7$, $R13$ and $R14$ are the two primary DOCRs. $R13$ is backed up by $R7$ while $R14$ is backed up by $R11$, $R21$, $R62$ and $R64$. Likewise,

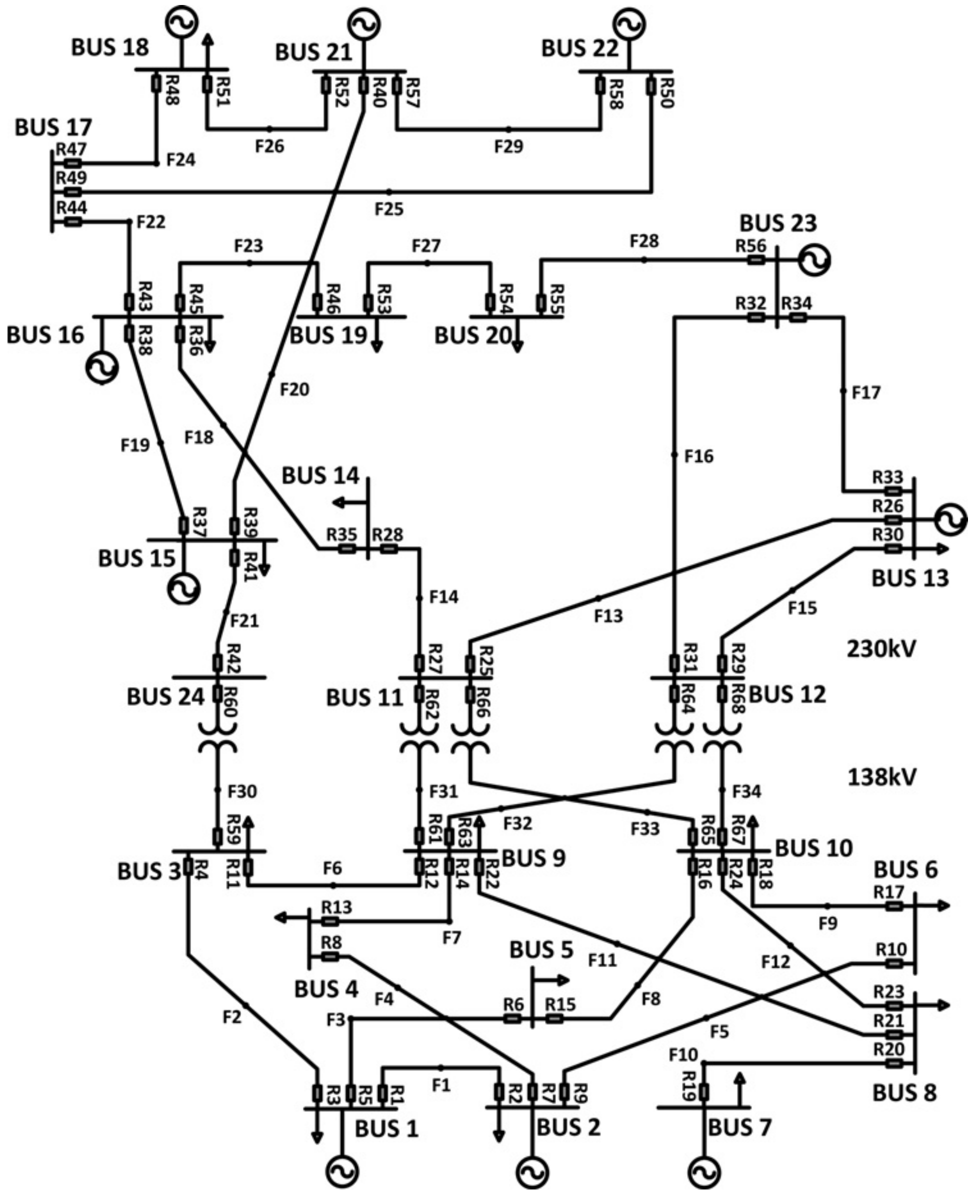

Fig. 2 *Power transmission system of the IEEE 24-bus RTS under study*

the primary and backup DOCRs for each fault location are defined and implemented in the PCO model.

The power distribution system chosen in this study is the distribution part of the IEEE 14-bus test system shown in Fig. 3 [27]. This distribution system is fed through two 60 MVA 132 kV/33 kV utility transformers with 10% transient reactance located at buses 1 and 2. Furthermore, two DG units are located at buses 5 and 6. Each DG unit is rated at 5 MVA and operates at unity power factor. These DG units are of the synchronous type with 9.67% transient reactance, and feed the system through a 480 V/33 kV step-up transformer with 5% transient reactance.

The system is equipped with 16 DOCRs. Eight Additional nodes are introduced ($F8 - F15$) to represent the fault locations. Similarly, each node is duplicated at different locations along the same line to accommodate for various coordination constraints sets and testing techniques simulated on this system.

Table 2 Generating units ratings and locations

Bus	Number of units	Units ratings, MW
1	4	20, 20, 76, 76
2	4	20, 20, 76, 76
7	3	all 100
13	3	all 197
15	6	all 12
16	1	155
18	1	400
21	1	400
22	6	all 50
23	3	155, 155, 350

3.2 *Solver and testing techniques description*

MATLAB optimisation toolbox containing minimum constrained non-linear multivariable function, in [28], is used to solve the PCO models. This built-in MATLAB function solves constrained NLP problems by using the reduced gradient approach (first order optimality). There are several algorithms available for solving a constrained NLP problem. The sequential quadratic programming (SQP) algorithm is chosen to solve the PCO models [20, 28]. A full description of the MATLAB SQP algorithm is provided in [29]. Fig. 4 presents a flowchart of the proposed algorithm used to determine the optimal relay settings as well as to check on any possible coordination violations. The algorithm starts by defining the coordination set to be used (from Table 1). Short circuit analysis is conducted and inputted to the optimisation model that

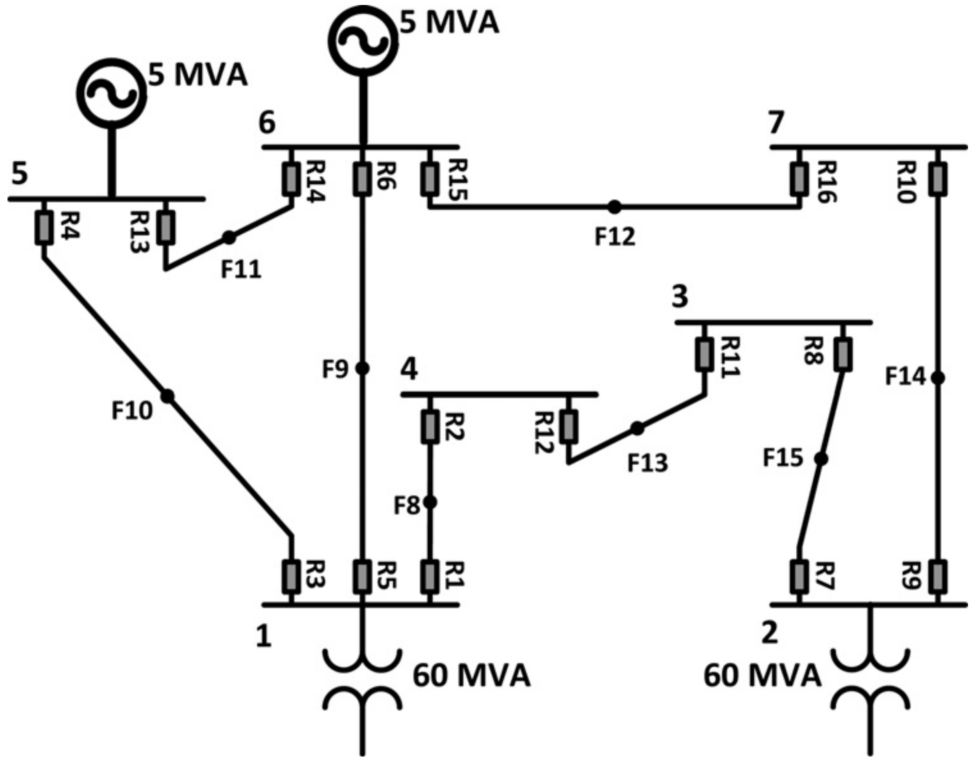

Fig. 3 *Power distribution system of the IEEE 14-bus system under study*

determines the relay settings. The optimal settings are then tested considering all possible fault locations. For example, the optimal relay settings obtained considering midway faults only (set 1 in Table 1) will then be tested on coordination constraints that involve all possible locations (set 5 in Table 1). This is done to check whether considering midway faults, for example, while obtaining the relay settings is sufficient for maintaining proper protection coordination at various fault points along the feeder. In cases where there are no violations in the protection coordination constraints, the optimal overall relay operating time is determined. It is worth noting that the proposed algorithm is executed offline. The attained optimal DOCR settings are utilised by the protection engineer to accordingly set the DOCRs. The operating time of the DOCR will be determined solely based on the equipped DOCR tripping characteristic with the respective pre-obtained settings.

4 Analysis of several coordination constraint sets

This section investigates the performance of the five coordination constraint sets on each of the test systems. In the first section, the optimal settings obtained by solving the PCO model considering each coordination set are presented. This is followed by a detailed analysis of the coordination violations resulted from the utilisation of the attained optimal relay setting from solving each PCO model. The second section presents the effect of different coordination constraint sets on the overall operating time *T*.

4.1 coordination constraints violation analysis

Multiple simulations were performed on both test systems where each simulation is based on one of the coordination constraint sets indicated in Table 1. The optimal DOCRs settings obtained, considering the various coordination sets, for the IEEE 14-bus distribution system are presented in Table 3. As can be seen from the results, the optimal TDS and I_p values vary depending on the coordination constraints set taken into consideration. Similar results were obtained for the IEEE 24-bus transmission system.

The algorithm, in Fig. 4, was applied to check the number of constraint violations for each coordination set. Thus, each set of optimal settings acquired, in Table 3, is tested to examine whether such settings will result in any violations when considering simultaneously faults at the near end, far end and each 10% of the line. For brevity, a detailed breakdown of the violated constraints because of coordination constraints set 2 (near-end) for the IEEE 14-bus distribution system is presented in Table 4. The violated coordination time (VCT) is the difference between the backup and the primary DOCR operating times (backup minus primary) involved in a violation. The violations have been classified into three types including normal, moderate, or severe violations. Normal violations will have a positive VCT value indicating that the primary DOCR operates before the backup DOCR but in a time less than the CTI value (which is 300 ms). On the other hand, negative VCT values are considered as moderate violations because in such cases the backup DOCR operates before the primary DOCR and thus coordination of these DOCRs is lost. Finally, severe violations occur when the backup DOCR does not operate and hence does not have a VCT value.

From the results, it is clear that the three types of coordination violations because of set 2 settings are present. There are 13 normal, one moderate and five severe violations. It can be seen that for almost all faults occurring at different locations on line 3–4 (denoted by $F12$ in Fig. 3), the coordination of the primary relay $R12$ and the backup relay $R1$ is violated (violations from 1 up to 10 in Table 4) except for relay $R12$ near-end fault ($F13_{99\%}$). It is also observed that the severity of these violations decreases as the location of the fault moves closer to $R12$. The reason behind this is that the optimal settings obtained for set 2 (given in Table 3) considers near end faults and thus no violations occurred for $F13_{99\%}$. This also explains the reason why VCT values in Table 4, for violations 1–10, decreases in value as the fault moves further away from $R12$. It can be seen that for $F13_{90\%}$ (at a distance of 10% from $R12$), primary $R12$ operates 291.8 ms before backup $R1$ that is slightly lower than the CTI value (300 ms). However, for $F13_{1\%}$ (at a distance of 99% from $R12$), primary $R12$ operates 31.7 ms before backup $R1$ which is very low with respect to CTI value.

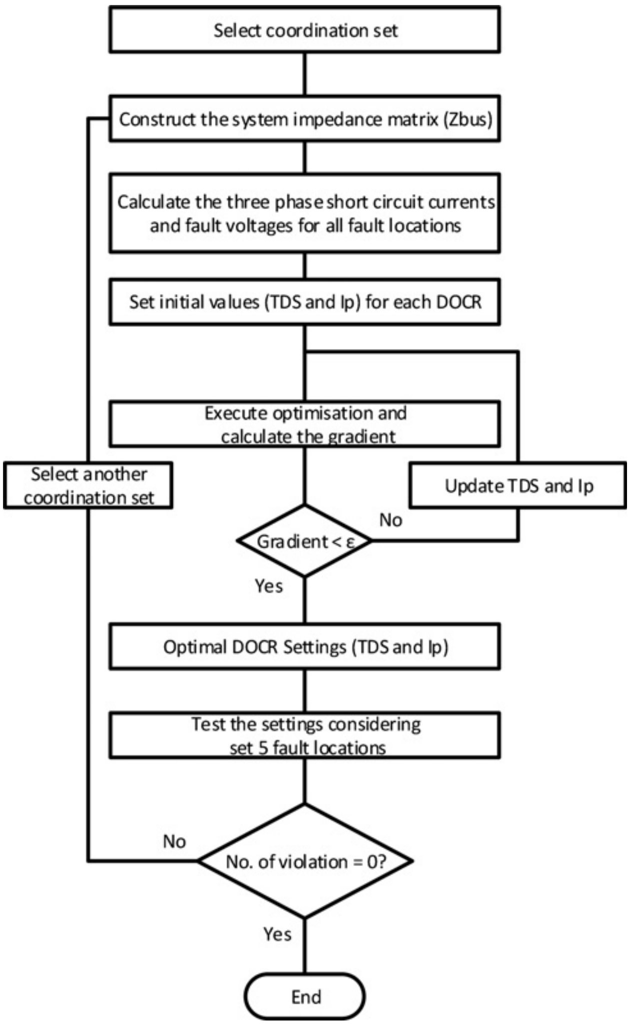

Fig. 4 *Algorithm flowchart for the protection coordination problem*

Another observation deduced is that for fault locations denoted by $F10$, severe violations occur near midway of the line 1–5 and a normal violation occur at far-end while no violations at other locations. Similar trend take place at $F9$ where severe violations occur near midway (violations 15–17) in addition to normal and moderate violations that come about towards the far-end, respectively.

These observations can be explained by examining the short circuit current seen by the DOCR because of different fault locations on the same line. To clarify this issue, $F9$ fault current at various locations on line 1–6 are presented. Since usually the main cause of coordination violations is the backup DOCR, Fig. 5 illustrates the short circuit current passing through backup relay $R4$ because of all $F9$ fault locations. It can be noted that the short circuit current passing through this backup relay does not have the expected linear relationship with the respective fault location. This parabolic effect is because of the meshed nature of the IEEE 14-bus system. Thus, it can be seen that fault currents because of near end faults for backup relays do not necessarily represent the maximum expected fault current seen by a relay. In addition, for some relays, the minimum fault current might not occur at the far end as in the case shown in Fig. 5 where the minimum fault current seen by relay $R4$ is approximately at 40% of the line length.

To further illustrate the coordination violations occurring because of the consideration of near-end fault locations only (set 2 coordination constraints), Figs. 6–8 show the inverse time current characteristic obtained by using the optimal settings of the primary DOCR $R5$ and backup DCOR R4 (Table 3-set 2) because of a three phase fault at $F9_{50\%}$, $F9_{90\%}$ and $F9_{99\%}$ of line 1–6, respectively. These three fault locations are chosen to demonstrate by the coordination graphs that normal, moderate and severe coordination violations, shown above in Table 4, occur because of the consideration of near-end fault locations only. It can be seen in Fig. 6 that because the pickup current setting of the backup DOCR $R4$ is higher than the short circuit current passing through it because of fault at $F9_{50\%}$, DOCR $R4$ does not operate and therefore is considered to be a severe coordination violation. Likewise, Fig. 7 shows that primary DOCR R5 (0.8318s) can

Table 4 IEEE 14-bus system coordination violations because of set 2 settings

Violation	Fault location	Primary	Backup	VCT, s
1	$F13_{1\%}$	$R12$	$R1$	0.0317
2	$F13_{10\%}$	$R12$	$R1$	0.0868
3	$F13_{20\%}$	$R12$	$R1$	0.1352
4	$F13_{30\%}$	$R12$	$R1$	0.1737
5	$F13_{40\%}$	$R12$	$R1$	0.2046
6	$F13_{50\%}$	$R12$	$R1$	0.2297
7	$F13_{60\%}$	$R12$	$R1$	0.2502
8	$F13_{70\%}$	$R12$	$R1$	0.2670
9	$F13_{80\%}$	$R12$	$R1$	0.2807
10	$F13_{90\%}$	$R12$	$R1$	0.2918
11	$F12_{99\%}$	$R15$	$R13$	0.2977
12	$F10_{40\%}$	$R3$	$R6$	—
13	$F10_{50\%}$	$R3$	$R6$	—
14	$F10_{99\%}$	$R3$	$R6$	0.1827
15	$F9_{30\%}$	$R5$	$R4$	—
16	$F9_{40\%}$	$R5$	$R4$	—
17	$F9_{50\%}$	$R5$	$R4$	—
18	$F9_{90\%}$	$R5$	$R4$	0.1230
19	$F9_{99\%}$	$R5$	$R4$	−0.0186

Table 3 Optimal TDS and I_p of each coordination constraint set for the IEEE 14-bus system

Relay	Set 1		Set 2		Set 3		Set 4		Set 5	
	TDS, s	I_p, pu	TDS, s	I_p, pu	TDS, s	I_p, pu	TDS, s	I_p, pu	TDS, s	I_p, pu
1	0.050	0.914	0.242	0.256	0.160	0.553	0.147	0.602	0.131	0.642
2	0.050	0.343	0.212	0.194	0.255	0.187	0.282	0.192	0.272	0.201
3	0.050	0.488	0.263	0.245	0.453	0.083	0.536	0.077	0.536	0.077
4	0.170	0.035	0.158	0.106	0.237	0.114	0.425	0.057	0.491	0.044
5	0.050	0.667	0.246	0.287	0.366	0.181	0.412	0.202	0.373	0.260
6	0.153	0.081	0.226	0.141	0.258	0.144	0.418	0.081	0.418	0.081
7	0.050	1.104	0.140	0.894	0.162	0.840	0.164	0.869	0.145	0.947
8	0.050	0.270	0.321	0.064	0.339	0.064	0.356	0.064	0.346	0.064
9	0.050	0.658	0.151	0.465	0.164	0.463	0.170	0.503	0.154	0.562
10	0.050	0.316	0.150	0.248	0.180	0.221	0.196	0.207	0.165	0.239
11	0.050	0.661	0.126	0.637	0.146	0.624	0.149	0.659	0.131	0.720
12	0.050	0.592	0.068	0.784	0.081	0.732	0.075	0.776	0.065	0.820
13	0.058	0.202	0.444	0.024	0.490	0.024	0.596	0.024	0.596	0.024
14	0.050	0.405	0.411	0.024	0.529	0.026	0.632	0.032	0.588	0.048
15	0.050	0.545	0.183	0.326	0.301	0.164	0.351	0.126	0.307	0.149
16	0.050	0.390	0.134	0.286	0.152	0.287	0.172	0.299	0.168	0.312

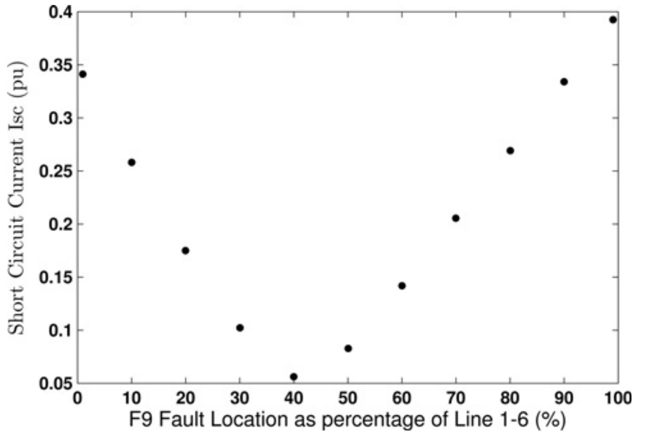

Fig. 5 *Short circuit current profile of R4 as a function of F9 fault locations*

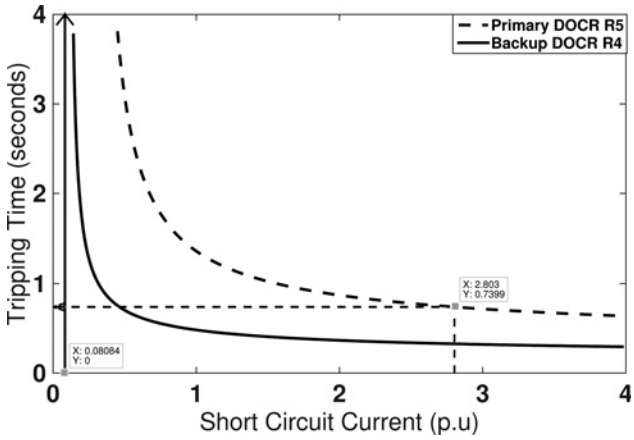

Fig. 6 *Inverse time current characteristics of the primary DOCR R5 and backup DOCR R4 with set 2 settings for a fault at $F9_{50\%}$ of line 1–6*

operate faster than backup DOCR R4 (0.9548s) for a fault at $F9_{90\%}$, but the time difference is less than the required CTI value which is 300 ms and hence is considered to be a normal coordination violation. Finally, Fig. 8 indicates that in case of a fault occurring at $F9_{99\%}$, the primary DOCR R5 (0.8548s) will operate after the backup DOCR R4 (0.8362s), and thus is considered to be a moderate coordination violation.

The total number of coordination constraints covering all fault locations in IEEE 14-bus and IEEE 24-bus systems are 242 and 1518 constraints, respectively. The number of constraints violated because of each set for both systems are shown in Table 5. It is clear that in both systems the total number of violations decreases as the coordination set becomes more inclusive. Although both sets 1 and 2 consider only one fault location on each line, coordinating based on near end faults (set 2) will result in much lower violations when compared with the midpoint fault analysis case (set 1). This indicates that the optimal settings obtained considering near end faults only can maintain feasibility across a broader range of fault locations on the same line. The numbers of violations significantly reduce when considering two fault locations simultaneously (set 3). Considering near-end, midpoint and far-end faults in the coordination problem will result in negligible violations (1 for the IEEE 14-bus and none for the IEEE 24-bus system).

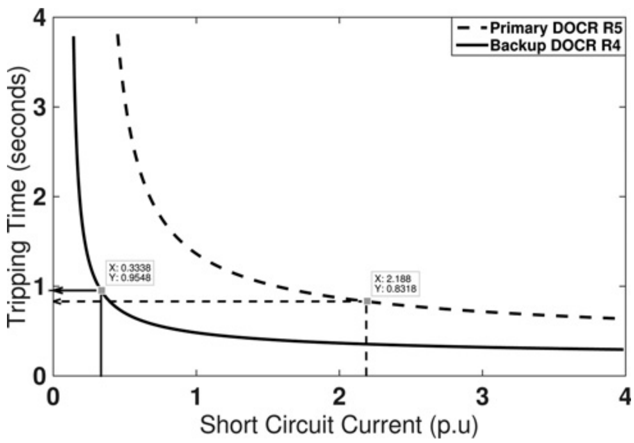

Fig. 7 *Inverse time current characteristics of the primary DOCR R5 and backup DOCR R4 with set 2 settings for a fault at $F9_{90\%}$ of line 1–6*

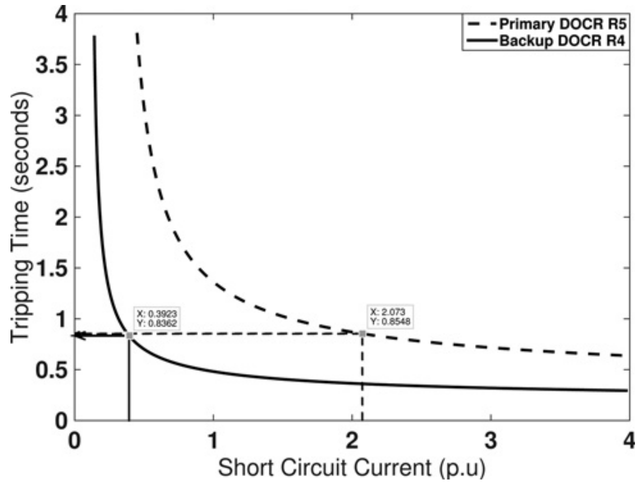

Fig. 8 *Inverse time current characteristics of the primary DOCR R5 and backup DOCR R4 with set 2 settings for a fault at $F9_{99\%}$ of line 1–6*

Although solving the PCO model based on set 4 for the IEEE 24-bus system results in no coordination violations, its resultant DOCR settings are not optimal. This can be seen by comparing the set 4 against set 5 DOCR settings in terms of overall tripping time T when both are tested for all fault locations. It is found that solving the PCO model based on set 5 results in a lower T value (5649 seconds overall operating time) than the case where set 4 is used (5960 seconds overall operating time). Therefore from this analysis, it is clear that the resultant solution obtained by solving the PCO model based on set 5 outperforms the solutions of the other sets in terms of accurate coordination of each DOCR for all fault locations and minimum overall relay time.

4.2 Overall operating time analysis

As seen from the above analysis, violations in coordination constraints can occur if the relay settings are determined

Table 5 Number coordination violations for all sets and systems

System	Set	Number of violations			
		Normal	Moderate	Severe	Total
IEEE 14-bus	1	96	0	12	108
	2	13	1	5	19
	3	0	0	5	5
	4	0	0	1	1
	5	0	0	0	0
IEEE 24-bus	1	331	2	9	342
	2	46	0	17	63
	3	0	0	15	15
	4	0	0	0	0
	5	0	0	0	0

Table 6 Comparison of total DOCR operating time

System	Fault locations investigated	Total DOCR operating time T, s	
IEEE 14-bus	midway only	set 1 28.168	set 5 76.539
	near-end only	set 2 31.636	set 5 41.293
	near-end/far-end	set 3 102.971	set 5 120.047
	near-end/midway/far-end	set 4 191.819	set 5 196.585
IEEE 24-bus	midway only	set 1 234.618	set 5 307.505
	near-end only	set 2 174.805	set 5 175.403
	near-end/Far-end	set 3 735.159	set 5 764.495
	near-end/midway/far-end	set 4 1395.8	set 5 1412.7

considering limited number of fault locations. The impact of determining the relay settings, taking into account multiple locations, on the overall relay time is given in Table 6. By applying the optimal settings obtained in Table 3 to specific locations on the system, it can be seen that set 5 results in higher overall relay operating time in comparison with the various sets.

Although the DOCR settings obtained by solving the PCO model considering set 5 achieves correct coordination of all DOCRs for all fault locations, a trade-off is that higher relay operating times will occur. Since both aspects (constraint violation and overall relay operating time) are significant in a protection coordination problem, a dual-setting characteristic is proposed to be utilised in DOCRs. This characteristic achieves reduction in T while solving the PCO model based on coordination constraints set 5 as will be explained in Section 5.

5 Proposed dual setting characteristic

This section discusses and analyses a dual-setting characteristic for DOCRs. The first section introduces the proposed relay characteristic. The latter section presents, compares and discusses the results attained by testing the proposed characteristic against the conventional characteristic on both the IEEE 14-bus distribution system and IEEE 24-bus transmission system.

5.1 Dual-setting characteristic description

The short circuit current, passing through each DOCR, varies depending on the fault locations. This complicates the protection coordination problem, as one set of DOCR settings is required to satisfy all coordination constraints, which involves a large range of short circuit currents. Therefore with the intention of easing the process, the proposed dual-setting characteristic involves dividing the range of short circuit currents into two equal sections. The lower set of short circuit currents utilise one set of DOCR settings (TDS_1 and I_{p1}) whereas the higher set of short circuit currents use the other set of DOCR settings (TDS_2 and I_{p2}). It is noted that two sections result in four DOCR settings that should be optimally determined. The number of settings will increase by increasing the number of sections. As a result, the number of decision variables in the PCO model increase (doubles in the case of dual setting characteristic). This can possibly cause a difficulty in solving the PCO model and consequently obtaining all of the optimal DOCR settings for large power systems by using deterministic optimisation techniques. In such situations, more advanced heuristic techniques might be required to solve such large complex optimisation problem. Hence, in this study, two sections have been selected to limit the number of settings per DOCR while achieving an improved performance than the conventional DOCR characteristic.

To implement the proposed characteristic, short circuit analysis should be carried out so as to compute the maximum short circuit current (I_{scmax}) and minimum short circuit current (I_{scmin}) passing through each DOCR because of all fault locations. The fault current midway between the above two aforementioned values (D) is then calculated as follows

$$D_i = I_{sci-\min} + \frac{(I_{sci-\max} - I_{sci-\min})}{2} \tag{7}$$

The proposed dual setting relay characteristic is equipped with one pair of setting for fault currents between I_{scmin} and D and the other pair of setting for fault currents between D and I_{scmax}. In other words, if the short-circuit current is lower than D, TDS_1 and I_{p1} DOCR settings is selected. Otherwise, if the short-circuit current magnitude is higher than D, TDS_2 and I_{p2} DOCR settings is selected. This 'if' statement condition can be modelled mathematically in an optimisation problem as follows

$$\begin{aligned} t_{ij} = {} & \mathrm{TDS1}_i \frac{A}{(I_{scij}/I_{p1i})^B - 1} \min(1, C^* \max(0, D_i - I_{scij})) \\ & + \mathrm{TDS2}_i \frac{A}{(I_{scij}/I_{p2i})^B - 1} \min(1, C^* \max(0, I_{scij} - D_i)) \end{aligned} \tag{8}$$

where each section of the equation is multiplied by a min/max selection function. This function along with the constant C (known in optimisation as the big M) that is set to a very large value (10 000 in this study), allow the selection between settings depending on the short circuit current sensed by the DOCR.

5.2 Performance of the dual-setting characteristic

The dual-setting characteristic is analysed in terms of coordination and DOCRs operating time. The new proposed relay is tested on the IEEE

Table 7 Optimal DOCR settings considering the dual-setting characteristic for the IEEE 14-bus system

Relay	TDS_1, s	I_{p1}, pu	TDS_2, s	I_{p2}, pu	I_{scmin}, pu	I_{scmax}, pu	D
1	0.050	0.951	0.058	0.077	1.247	3.837	2.542
2	0.086	0.216	0.050	0.077	0.476	1.522	0.999
3	0.107	0.245	0.060	0.077	0.410	4.374	2.392
4	0.249	0.035	0.056	0.035	0.056	1.534	0.795
5	0.096	0.398	0.050	0.181	0.562	3.976	2.269
6	0.193	0.081	0.050	0.081	0.091	1.784	0.937
7	0.051	0.997	0.050	1.059	1.536	3.406	2.471
8	0.175	0.064	0.050	0.417	0.220	1.239	0.729
9	0.076	0.444	0.054	0.098	0.808	3.693	2.250
10	0.169	0.098	0.050	0.098	0.417	1.249	0.833
11	0.065	0.511	0.059	0.047	0.933	2.520	1.727
12	0.059	0.635	0.055	0.047	1.011	1.951	1.481
13	0.263	0.024	0.065	0.024	0.043	1.875	0.959
14	0.373	0.024	0.073	0.024	0.069	3.159	1.614
15	0.055	0.521	0.058	0.063	0.697	3.016	1.856
16	0.050	0.370	0.050	0.063	0.476	1.634	1.055

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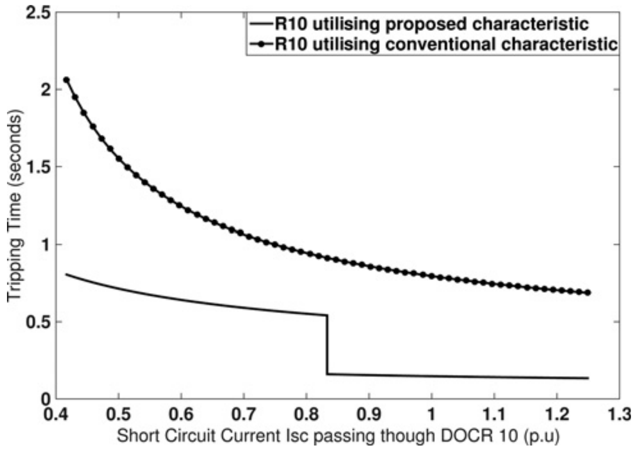

Fig. 9 *R10 dual-setting and conventional characteristics*

14-bus and IEEE 24 bus systems. For brevity, Table 7 shows the IEEE 14-bus distribution system optimal DOCR settings along with maximum, minimum and boundary short circuit current values for each DOCR. It is observed that the optimal TDS values obtained for the proposed characteristic in Table 7 are significantly lower than the optimal values attained for the conventional characteristic in Table 3-set 5. Fig. 9 illustrates the conventional and proposed characteristic curves for one of the relays namely $R10$, in the IEEE 14-bus system, with their optimal settings shown in Table 3-set 5 and Table 7, respectively. It is clear that when DOCR $R10$ utilises the proposed relay characteristic achieves much faster operating times than when $R10$ utilises the conventional relay characteristic for all fault currents passing through it.

Table 8 shows a breakdown of IEEE 14-bus system DOCR's operation times for fault locations that occur at $F_{25\%}$ of each line considering both the conventional and proposed DOCR characteristics. From the results, it is clear that even though fault location $F_{25\%}$ is not part of the fault locations considered in set 5, all primary and backup DOCRs are correctly coordinated with a minimum value of 300 ms for CTI. Moreover, it can be seen that the relay tripping times obtained from the proposed relay characteristic for each DOCR is always faster than the times attained from the conventional relay characteristic. Similar observations have been noted for other non-coordinated fault locations for both test systems.

Finally, Table 9 presents a comparison between the proposed and conventional characteristic in terms of the overall DOCRs operating time T for all fault locations. The results clearly indicate that the dual-setting characteristic achieves significant reduction in T when

Table 8 Optimal primary and backup DOCR operating times of IEEE 14-bus because of conventional and proposed relay characteristic

Fault location	Operating times of relays, s (p = primary, b = backup)					
	Conventional characteristic			Proposed characteristic		
	p	$b1$	$b2$	p	$b1$	$b2$
$F8_{25\%}$	$R1$: 0.57	$R4$: 1.83	$R6$: 1.45	$R1$: 0.10	$R4$: 0.82	$R6$: 0.67
	$R2$: 1.12	$R11$: 2.31	—	$R2$: 0.13	$R11$: 0.61	—
$F9_{25\%}$	$R5$: 1.00	$R2$: 1.40	$R4$: 2.98	$R5$: 0.12	$R2$: 0.47	$R4$: 1.25
	$R6$: 1.11	$R13$: 2.18	$R16$: 1.82	$R6$: 0.13	$R13$: 0.96	$R16$: 0.74
$F10_{25\%}$	$R3$: 0.97	$R2$: 1.49	$R6$: 2.13	$R3$: 0.11	$R2$: 0.50	$R6$: 0.98
	$R4$: 1.21	$R14$: 1.87	—	$R4$: 0.13	$R14$: 0.89	—
$F11_{25\%}$	$R13$: 0.96	$R3$: 1.32	—	$R13$: 0.11	$R3$: 0.46	—
	$R14$: 1.15	$R5$: 2.28	$R16$: 2.34	$R14$: 0.12	$R5$: 0.95	$R16$: 1.06
$F12_{25\%}$	$R15$: 0.76	$R5$: 1.45	$R13$: 1.33	$R15$: 0.11	$R5$: 0.49	$R13$: 0.59
	$R16$: 1.02	$R9$: 1.95	—	$R16$: 0.12	$R9$: 0.67	—
$F13_{25\%}$	$R11$: 0.82	$R7$: 1.19	—	$R11$: 0.10	$R7$: 0.44	—
	$R12$: 0.86	$R1$: 1.19	—	$R12$: 0.53	$R1$: 0.93	—
$F14_{25\%}$	$R9$: 0.65	$R8$: 0.99	—	$R9$: 0.11	$R8$: 0.50	—
	$R10$: 0.91	$R15$: 1.22	—	$R10$: 0.16	$R15$: 0.81	—
$F15_{25\%}$	$R7$: 0.83	$R10$: 1.22	—	$R7$: 0.32	$R10$: 0.64	—
	$R8$: 0.84	$R12$: 1.72	—	$R8$: 0.37	$R12$: 0.80	—

Table 9 Comparison of dual-setting and conventional characteristic

System	Total DOCR operating time, s		Percentage reduction, %
	Conventional	Dual-setting	
IEEE 14-bus	630.10	240.24	61.87
IEEE 24-bus	5648.8	4414.3	21.85

implemented on both test systems while maintaining feasible coordination across multiple locations on each feeder.

6 Conclusion

This paper first investigates the impact of the fault locations considered in modelling the coordination constraints on the feasibility of the protection coordination problem. The results reveal that coordination constraints are violated when the protection coordination problem is solved considering one fault location (midway for example), two fault locations and even three fault locations on each line. The severity and number of violations vary depending on the number of fault locations considered. It has been shown that, to assure proper coordination along the various points on a feeder, coordination constraints involving multiple fault locations should be included in the protection problem. This will guarantee optimal feasible solutions but on the expense of relay operating time. To achieve feasible coordination while maintaining minimum relay operating time, a dual-setting DOCR characteristic is proposed that provides two sets of settings based on the short circuit current passing through each DOCR. The proposed characteristic was tested on both the IEEE 14-bus and 24-bus systems considering multiple fault locations across each feeder. The results show that by utilising the dual-setting characteristic as opposed to the conventional characteristic, significant reduction in the overall DOCRs operating time is achieved while maintaining feasibility.

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