Coordination of non-directional overcurrent relays and fuses in active distribution networks considering reverse short-circuit currents of DGs

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Abstract
The main protection equipment in radial distribution networks are non-directional overcurrent relays (NDOCR) and fuses which are coordinated using the conventional overcurrent coordination method. By installing distributed generations (DGs) in the network, reverse short-circuit currents (SCC), injected from DGs, can lead to false tripping of NDOCRs and false melting of fuses. In the previous studies, some methods have been proposed to overcome these issues using directional overcurrent relays, fault current limiter, and adaptive methods that relay on communication. The present paper proposes a new coordination method to prevent these issues without the need for installing a new equipment, by proposing a new set of selectivity constraints. Here, selectivity between equipment is established, and false tripping and false melting issues are mitigated. The coordination of protection equipment according to the proposed method requires the use of optimization algorithms, and therefore, the proposed method is formulated as a mixed-integer linear programming method to take advantage of mathematical optimization algorithms. The proposed coordination method is applied to a real distribution network and the results indicate the high efficiency of the proposed method in dealing with false relay tripping and fuse melting issues.

1 INTRODUCTION
Non-directional overcurrent relays (NDOCRs) and fuses are the main protection equipment for radial distribution networks. Since these equipment are non-directional, reverse short-circuit currents (SCCs) injected by distributed generations (DGs) in active distribution networks can affect their operation, in the form of false tripping of NDOCRs and false melting of fuses. When a fault occurs on a feeder, the injected SCCs from the DGs in the reverse direction can cause fuse melting or tripping of NDOCRs installed on healthy feeders. The simplest approach to eliminate the effect of DGs on the protection of distribution networks is by separating the DGs from the network when a fault occurs [1], however, this strategy reduces system reliability. Another solution is to limit the capacity of the DGs but this would limit benefiting from the advantages of the DG installation [2]. A control scheme has been proposed in [3] which uses a solid-state switch-based field discharge circuit for limiting the SCC of synchronous DG (SDG). The SCC of inverter-based DGs can be reduced to the rated current by its inverter's control and thus reducing its impacts on protection [4]. The use of fault current limiter (FCL) is another way of eliminating the impact of DGs [5–7].

New protection schemes, such as adaptive over current (OC) protection [8, 9] and OC protection via communication link [10] have been presented to resolve the impact of DGs on the protection of distribution networks. In addition, new characteristic curves have been defined for OC relays which eliminate the effect of DGs on OC protection. Voltage–current–time [11, 12], discrete current–time [13], non-standard current–time
Various sources can cause false tripping issues like the contribution of induction motors to SCC in industrial networks [18], and reverse SCC injected by DGs in active distribution networks [15]. Since the location and the size of the DG can affect the false tripping issue, DGs can be allocated in such a way that false tripping can be eliminated [19]. The method, in [5], determines the size and location of FCLs in addition to the settings of the equipment considering anti-false melting and anti-false tripping constraints. These constraints are proposed such that NDOCRs and fuse are coordinated in such a way that pickup current setting (PC3) of NDOCRs and minimum melting current of fuse (MMC) of fuses are larger than the maximum reverse SCCs seen by NDOCRs and fuses. In [15], other settings in addition to PCY are obtained for the NDOCRs on healthy feeders such that their operating times (OTs) for reverse SCCs injected by DGs are larger than the OT of primary NDOCR at the faulty feeder. In [18], a coordination method based on a dynamic model of OC relays is proposed in order to prevent the false tripping issue caused by the contribution of induction motors to the SCC in industrial networks.

Most OC protection schemes use optimization algorithms (intelligent and mathematical) to obtain the protection equipment’s settings. Genetic algorithm (GA) [20], symbiotic organisms search (SOS) [21], ant colony optimization [22], particle swarm optimization (PSO) [23], biogeography-based optimization (BBO) [24] and simulated annealing algorithm [25] are examples of intelligent algorithms applied to the protection coordination problem. In addition, mathematical algorithms including linear programming [26], mixed-integer linear programming [27–29], binary programming [30] and quadratic programming [31] have also been applied to determine the optimal protective device settings.

False tripping of NDOCRs and false melting of fuses are the main impacts of installing DGs on the protection coordination, many attempts have been devoted to consider them, in the previous studies. The aim of this paper is proposing a coordination method to overcome these issues by defining and adding new selectivity constraints (relay–relay, relay–fuse, fuse–relay and fuse–fuse) without the need for installing new costly equipment in the network. The conventional protection coordination method for radial distribution network is based on the coordination of the protective devices one by one from downstream to upstream. But, due to the new set of selectivity constraints, an optimization method is required to solve the proposed protection coordination algorithm. Therefore, the new method is formulated based on Mixed Integer Linear Programming (MILP) optimization algorithm, due to its advantages such as high optimality of results and high solving speed. In the previous studies, the coordination of OC relays has been presented using MILP. In this paper, the algorithm is developed to consider fuse equations and the non-linear equations for the coordination of NDOCRs and fuses are linearized to be solved in the MILP-based protection coordination algorithm. The new method is applied on a real radial distribution network and the results are compared with the results of previous methods. The contributions of this paper have been listed as below:

- Presenting a new coordination method for preventing false tripping of NDOCRs and false melting of fuses without using additional equipment
- Linearizing the proposed method for solving with MILP approach

The structure of the paper is as follows: Section 2 describes the problem statement and proposed coordination method. In Section 3, the proposed coordination method is formulated based on MILP. Simulation results are presented and analysed in Section 4. Section 5 draws the conclusions.

2 | PROBLEM STATEMENT AND PROPOSED METHOD

A comparison of various protection schemes for a distribution network in the presence of DGs can be seen in Table 1. A passive distribution network is shown in Figure 1. In the event of a fault, only overcurrent protection equipment located upstream of the fault can sense the SCC. Also, all SCCs pass through the equipment in a forward direction. In this case, considering selectivity constraints between the operation of backup fuse and primary fuse in (1), backup NDOCR and primary fuse in (2), and backup NDOCR and primary NDOCR as (3) would be enough for the coordination of overcurrent protection equipment. Using only these constraints for designing an overcurrent protection scheme is denoted as the ‘conventional coordination method’ in this paper. The coordination constraints for the OC relays and fuses are presented in [5] and [32].

\[ MCT_p(IP(\tau_p)) \leq 0.75 \times MMT_p(IB(\tau_p)) \]  

(1)
TABLE 1 Comparison of various protection schemes for a distribution network in the presence of DGs

| Technique                                | Merits                                           | Demerits                                      |
|------------------------------------------|--------------------------------------------------|-----------------------------------------------|
| Disconnection of DG after fault [1]      | - Prevent miss-coordination                       | - Reducing reliability                        |
|                                          | - Prevent relay false trip                        | - May lead to severe voltage sags as the contribution of reactive power from DGs will be cut off |
|                                          |                                                   | - Stability problem may occur if there were high penetrations of DGs in the network |
|                                          |                                                   | - Disconnecting of DGs is not useful for temporary fault |
| Limitation of DG capacity [2]            | - Prevent miss-coordination                       | - Unable to use full DG capacity              |
| Modification of the protection scheme    | - Prevent relay false trip                        | - This method does not consider fuse false blowing |
| Adaptive OC protection [8, 9]            | - Prevent miss-coordination                       | - Reduces reliability because it uses communication links |
|                                          | - Prevent relay false trip                        | - Increases cost because of using intelligent electronic devices and communication links |
|                                          |                                                   | - This method does not consider fuse false blowing |
| Communication based protection [10]      | - Prevent miss-coordination                       | - Reduces reliability because it uses communication links |
|                                          | - Prevent relay false trip                        | - Increases cost because of using communication links |
|                                          |                                                   | - This method does not consider fuse false blowing |
| New characteristic curve of OCR [15]     | - Prevent miss-coordination                       | - This method does not consider fuse false blowing |
|                                          | - Prevent relay false trip using new constraint and non-standard curve for relay |                                                 |
| Reduction of SCC of DG                   | - Prevent miss-coordination                       | - Special application for synchronous DG      |
| Using solid-state switch-based field discharge circuit [3] | - Prevent relay false trip                        | - This method does not consider fuse false blowing |
| Using inverter’s control [4]             | - Prevent miss-coordination                       | - Special application for inverter-based DG   |
|                                          | - Prevent relay false trip                        | - This method does not consider fuse false blowing |
| Using FCL [5, 6]                        | - Prevent miss-coordination                       | - Increases cost because of using FCL         |
|                                          | - Prevent relay false trip                        | - This method does not consider fuse false blowing |

The selectivity constraints given in (1)–(3) are valid for active distribution networks, however, they are not sufficient for addressing reverse SCCs injected by DGs. Figure 2 demonstrates SCCs injected by multiple sources in an active distribution network for SCs in various protection zones. SCC passing through equipment, not located at the upstream of the SC, and SCC passing through the overcurrent protection equipment in the backward direction impose major protection coordination issues. During these short-circuit (SCs), there is a possibility that the injected reverse SCCs from DG1 and DG2 cause false melting and false tripping of fuses and NDODRs.

2.1 False fuse melting

This issue is presented and highlighted considering the false melting of fuses for a fault in the protection zone of relays and other fuses. Figure 3 shows the false melting of fuse F7 before the operation of relay R5 for a SC in \( \zeta_{RS} \) because of the reverse SCC of DG1 (\( \Delta t_{\text{false}} = MMT_{\text{F7}}(IR_{F7}(\zeta_{RS})) - t_{R5}(I_{PR5}(\zeta_{RS})) \leq 0 \)). To avoid this issue, it is suggested that new selectivity constraints given in (4) be added to the conventional constraints given in (1)–(3). Establishment of constraint (4) guarantees that the minimum melting time (\( MMT \)) of the fuse which senses the reverse SCC is greater than the OT of primary NDOCR for a SC occurring in the relay’s protection zone. According to Figure 3, using the proposed constraints, fuse F7 acts later than R5 for a SC in \( \zeta_{RS} \) by considering the selectivity constraint (4), and as a result, the false melting of F7 is mitigated.

\[
\begin{align*}
MCT_p(IP(\zeta_p)) + CTI1 & \leq t_p(IB(\zeta_p)) \\
MCT_p(IP(\zeta_p)) + CTI1 & \leq t_p(IB(\zeta_p)) \\
t_p(IP(\zeta_p)) + CTI2 & \leq t_p(IB(\zeta_p)) \\
t_p(IP(\zeta_p)) + CTI2 & \leq t_p(IB(\zeta_p))
\end{align*}
\]

Figure 4 shows the operation of F7 and F8 for SC in \( \zeta_{RS} \). It is clear that if \( FT \) of F7 is set based on the conventional method, F7 melts before clearing the SC by F8 (\( \Delta t_{\text{false}} = MMT_{\text{F7}}(IR_{F7}(\zeta_{RS})) - MCT_{F8}(I_{PR8}(\zeta_{RS})) \leq 0 \)). The false melting of fuse for a SC in the protection zone of another fuse can be prevented by adding a new selectivity constraint given in (5) to the pre-existing selectivity constraints. This
constraint guarantees that the $\text{MMT}$ of the fuse, experiencing reverse SCC, is greater than the $\text{MCT}$ of the primary fuse. As can be seen in Figure 4, the false melting issue is mitigated considering the proposed constraints for F7.

\[
\text{MCT}_P(\text{IP}(\tau_p)) \leq 0.75 \times \text{MMT}_F(\text{IR}(\tau_p))
\] (5)

### 2.2 False tripping of NDOCRs

Figure 5 demonstrates the false tripping of R4, using the setting obtained which uses the conventional method, where R4 clears the fault before R5 and F8 for SC in $z_{R_5}$ and $z_{F_8}$. As can be seen, R4 operates faster than R5 and F8 for SCs in their protection zones. Adding new selectivity constraints given in (6) and (7) to the previous constraints can guarantee and mitigate the false tripping of NDOCRs. Constraints (6) and (7), respectively, illustrate that OT of the NDOCR which senses reverse SCC must be greater than OT of the primary NDOCR or $\text{MCT}$ of primary fuse given an SC occurs in its protection zone. As can be seen in Figure 5, the obtained protective device settings using the new constraints in (6) and (7) mitigate the false tripping of R4.

\[
\begin{align*}
\text{t}_P(\text{IP}(\tau_p)) + \text{CTI}_2 &\leq \text{t}_P(\text{IR}(\tau_p)) \quad (6) \\
\text{MCT}_P(\text{IP}(\tau_p)) + \text{CTI}_1 &\leq \text{t}_P(\text{IR}(\tau_p)) \quad (7)
\end{align*}
\]

### 2.3 Proposed coordination method as an optimization problem

In conventional radial distribution networks, the coordination of OC equipment can be achieved without the need for using...
Subject to:

\[ \text{Establishing constraints } (1) - (7) \]  

\[ TMS_{i,j}^{\text{min}} \leq TMS_{i,j} \leq TMS_{i,j}^{\text{max}} \]  

\[ \max \left( PCS_{i,j}^{\text{min}}, I_f^{\text{max}} \right) \leq PCS_{i,j} \]  

\[ PCS_{i,j} \leq \min \left( PCS_{i,j}^{\text{max}}, I_f^{\text{min}} \right) \]  

\[ I_f^{\text{max}} < MMC \left( FT_i \right) \]  

\[ RT_i \in \text{Standard characteristics} \]  

\[ FT_i \in \text{Specified types} \]  

3. FORMULATION OF PROPOSED COORDINATION METHOD BASED ON MILP

In order to achieve the benefits of mathematical optimization algorithms, and therefore, solve the proposed coordination problem by MILP, \( MMT \) and \( MCT \) of the fuse for various \( FT \)s, and OT of NDOCR for various \( TMS \)s, \( PCS \)s and \( RT \)s are reformulated and modelled with linear formulations.

3.1 Linearization of \( MMT \) and \( MCT \) of fuse

All possible \( FT \)s of fuse \( i \) are stored in \( FT_i \) as (9), and the corresponding binary variable for each \( FT \) is defined as \( x_{\text{fus}}^{i,g} \). If \( x_{\text{fus}}^{i,g} \) is equal to one, \( g \)th type of fuse \( i \) will be selected. Since only one \( FT \) must be selected for each fuse, equality constraint (10) should be considered.

\[ \text{Subject to:} \]

\[ (9) \]

\[ (10) \]
Therefore, 1 binary variable for fuse \( i \) must be considered as given in (13).

\[
x_{i,1}^{rel} \times \cdots \times x_{i,n}^{rel}
\]

(13)

### 3.2 Linearization of OT of NDOCR

All possible combinations of discrete values of \( RCS \), and various \( RT \)’s for NDOCR \( i \) are stored in the \( PT_i \), and one corresponding binary variable is assigned in \( x_{i,rel}^{rel} \) for each combination as shown in (14). For instance, binary variable \( x_{i,rel}^{rel} \) corresponds to \( j \)th discrete value of \( RCS \) and \( k \)th type of \( RT \); and these settings are chosen as optimal settings of NDOCR \( i \) when \( x_{i,rel}^{rel} \) is equal to one. The equality constraint (15) guarantees that only one combination is chosen as an optimal setting for NDOCR \( i \). The OT of NDOCR \( i \) are given in (16).

\[
PT_i = \left[ \left( RCS_{i,1} \right) \cdots \left( RCS_{i,n} \right) \left( RT_{i,1} \right) \cdots \left( RT_{i,n} \right) \right]
\]

(14)

\[
x_{i}^{rel} = \left[ x_{i,1,rel}^{rel} \times \cdots \times x_{i,n,rel}^{rel} \right]
\]

(15)

\[
t_i \left( If \right) = \sum_{b=1}^{n_{\text{XOR}}} c_{i,k}^{rel} \times x_{i,b}^{rel} \cdot TM_S
\]

(16)

It is clear from (16) that the OT of NDOCR \( i \) is not linear. In this case, the linearization method mentioned in (17) must be used. In (17), multiplication of a binary variable \( u \) and continuous variable \( v \) is replaced by a continuous linear variable \( V \), by adding two constraints (17b) and (17c) to the pre-existing constraints.

\[
u \times v_{\text{min}} \leq V \leq u \times v_{\text{max}}
\]

(17b)

\[
v - (1 - u) \times v_{\text{min}} \leq V \leq v - (1 - u) \times v_{\text{max}}
\]

(17c)

By applying the linearization method in (17) to (16), \( x_{i,b}^{rel} \cdot TM_S \) is replaced with \( X_{i,b}^{rel} \) as in (18). According to (17b), \( X_{i,b}^{rel} \) will be zero if \( x_{i,b}^{rel} \) is equal to zero. Similarly, according to (17c), \( X_{i,b}^{rel} \) will be equal to \( TM_S \) if \( x_{i,b}^{rel} \) is equal to one. According to (18), OT of NDOCR \( i \) for various values of \( TM_S, RCS \) and \( RT \) is modelled by linear variables.

\[
t_i \left( If \right) = \sum_{b=1}^{n_{\text{XOR}}} c_{i,k}^{rel} \times X_{i,b}^{rel}
\]

(18)

Defined binary and continuous variables for NDOCR \( i \) are presented in (19).

\[
x_{i,1,rel}^{rel} \times \cdots \times x_{i,n,rel}^{rel} \times X_{i,rel}^{rel} \times TM_S
\]

(19)

### 3.3 Presentation of proposed method in MILP form

In the previous part, \( MMT \) and \( MCT \) of fuses and OT of NDOCRs are expressed based on linear variables. In this case, MILP can be used to solve the proposed coordination method. The OF of the MILP for the proposed coordination method is highlighted in (20a), and the constraints (20b–20h) are a converted form of selectivity constraints (1–7). Equations (20i–20l) are constraints added because of the linearization process. \( bp1, bp2 \) and \( bp3 \) are pairs of backup and primary equipment for coordination of fuse–fuse, relay–fuse and relay–relay, respectively. \( rp1 \) and \( rp2 \) are pairs of fuse–relay and fuse–fuse used for avoiding the false melting of fuses; and, \( rp3 \) and \( rp4 \) are pairs of relay–relay and relay–fuse used for avoiding the false tripping of NDOCRs. \( \zeta, \varphi \) and \( \tau \) are constant values and are obtained from (11), (12) and (16). Figure 6 shows the flowchart of the proposed coordination algorithm using MILP.

\[
\text{OF} : \sum_{i=1}^{l} \sum_{g=1}^{n_{\text{XOR}}} \theta_{i,g}^{BP} \times x_{i,g}^{rel} + \sum_{i=1}^{l} \sum_{b=1}^{n_{\text{XOR}}} \left( \tau_{i,b}^{BP} + \tau_{i,b}^{RP} \right) \times X_{i,b}^{rel}
\]

(20a)

Subject to:

\[
\sum_{i=1}^{l} \sum_{g=1}^{n_{\text{XOR}}} \phi_{i,g}^{BP} \times x_{i,g}^{rel} \leq 0.75 \sum_{i=1}^{l} \sum_{g=1}^{n_{\text{XOR}}} \theta_{i,g}^{BP} \times x_{i,g}^{rel}
\]

(20b)

\[
\sum_{i=1}^{l} \sum_{g=1}^{n_{\text{XOR}}} \phi_{i,g}^{BP} \times x_{i,g}^{rel} + CTI \leq \sum_{b=1}^{n_{\text{XOR}}} \tau_{i,b}^{BP} \times X_{i,b}^{rel}
\]

(20c)

\[
\sum_{i=1}^{l} \sum_{g=1}^{n_{\text{XOR}}} \phi_{i,g}^{BP} \times x_{i,g}^{rel} + CTI \leq \sum_{b=1}^{n_{\text{XOR}}} \tau_{i,b}^{RP} \times X_{i,b}^{rel}
\]

(20d)
4 | SIMULATION RESULTS

The proposed coordination method is applied to the 20 kV Sirjan distribution network located in Iran. This network consists of two main feeders fed by a 63/20 kV substation, containing 125 branches and 77 residential, industrial and commercial loads. This network has been simplified as a 19 bus network in Figure 7 [19], where four SDGs with capacities of 6, 3, 4 and 5 MVA are assumed to be installed. Transient reactances of these SDGs are 0.1, 0.12, 0.11 and 0.09 p.u., respectively [33]. OC protection of this network includes 6 NDOCRs and 12 fuses. \( \mathbf{bp} \) and \( \mathbf{rp} \) matrices of this network are mentioned in (21). Minimum amounts of pickup current settings (RCs) for 6 NDOCRs are 400, 150, 250, 125, 50, 150 and 50 A, respectively. It is considered that RCs of NDOCRs can be increased up to four times of minimum amounts in steps of 0.1. Available RCs and FT's are listed in Tables 2 and 3, respectively [34]. \( \text{CTI}_1 \) and \( \text{CTI}_2 \) are considered to be 0.2 and 0.3 s, respectively.

\[
\mathbf{bp} = \{(1, 2), (1, 3), (2, 4), (2, 5), (3, 6), (6, 7)\}
\]  
\[
\mathbf{bp}^2 = \{(3, 8), (4, 9), (4, 10), (6, 11)\}
\]
The obtained settings from the conventional method (not considering new constraints) and the proposed method (conventional constraints in addition to new ones) considering 16 cases including connection or disconnection of DGs are listed in Table 4. The mentioned time differences in Tables 5 and 6 are differences between the melting time of fuses \( t_{MC} \) and \( t_{MMTr} \) for reverse SCCs with clearing time of primary fuses \( MCT_m \) or OT of primary NDOCRs \( t_1 \) for maximum SC occurring in the primary equipment protection zones. In the conventional method, the coordination of protection devices is considered without the false trip impact of DGs, so the constraints (1)–(3) are only considered and solved by both MILP and GA. As can be seen from Table 4, the OF of the proposed method is larger than that of the conventional method. However, the false melting and the false tripping issues have been resolved. Referring to Tables 5 and 6, all operating time differences for the proposed method are positive amounts, therefore, the proposed method is capable of mitigating the false melting and the false tripping issues.

Figure 8 demonstrates the operation of F10, R5 and F9 for maximum three-phase SC occurring in \( z_{F,10} \). It can be seen that F9 and R5 with the settings obtained from the conventional

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**TABLE 2** Various RTs according to IEC 60255-151 standard

| No. | RT | Formula | \( c \) | \( d \) |
|-----|----|---------|--------|--------|
| 1   | SI | \( r = \frac{3000}{(p/7)} \) | 0.14   | 0.02   |
| 2   | VI | 13.5    | 1      |        |
| 3   | EI | 80      | 2      |        |

\[
bp^3 = \left\{ (8, 12), (8, 13), (10, 14), (10, 15), (11, 16), (11, 17), (16, 18) \right\} \tag{21c}
\]

\[
bp^4 = \left\{ (8, 2), (8, 4), (8, 5), (8, 6), (8, 7), (9, 3), (9, 5), (9, 6), (9, 7), (13, 2), (13, 4) \right\} \tag{21d}
\]

\[
rp^2 = \left\{ (8, 9), (8, 10), (8, 11), (8, 14), (8, 15), (8, 16), (8, 17), (8, 18), (9, 8), (9, 10), (9, 11), (9, 12), (9, 13), (9, 14), (9, 15), (9, 16), (9, 17), (9, 18), (13, 9), (13, 10), (13, 11), (13, 12), (13, 14), (8, 15), (8, 16), (13, 17), (13, 18) \right\} \tag{21e}
\]

\[
rp^3 = \left\{ (2, 3), (2, 6), (2, 7), (3, 2), (3, 4), (3, 5), (4, 3), (4, 5), (4, 6), (4, 7), (5, 3), (5, 4), (5, 6), (5, 7), (6, 2), (6, 4), (6, 5), (7, 2) \right\} \tag{21f}
\]

\[
rp^4 = \left\{ (2, 8), (2, 11), (2, 12), (2, 13), (2, 16), (2, 17), (2, 18), (3, 9), (3, 10), (3, 14), (3, 15), (4, 8), (4, 11), (4, 12), (4, 13), (4, 16), (4, 17), (4, 18), (5, 8), (5, 9), (5, 10), (5, 11), (5, 12), (5, 13), (5, 14), (5, 15), (5, 16), (5, 17), (5, 18), (6, 8), (6, 9), (6, 10), (6, 12), (6, 13), (6, 14), (6, 15), (7, 8), (7, 9), (7, 10), (7, 11), (7, 12), (7, 13), (7, 14), (7, 15), (7, 16), (7, 17), (7, 18) \right\} \tag{21g}
\]

**TABLE 3** Various FTs according to [34]

| No. | FT   | No. | FT   |
|-----|------|-----|------|
| 1   | 16K  | 11  | 200K |
| 2   | 25K  | 12  | 224K |
| 3   | 36K  | 13  | 250K |
| 4   | 50K  | 14  | 300K |
| 5   | 63K  | 15  | 355K |
| 6   | 80K  | 16  | 400K |
| 7   | 100K | 17  | 500K |
| 8   | 125K | 18  | 600K |
| 9   | 140K | 19  | 800K |
| 10  | 160K | 20  | 1000K |
TABLE 4  Settings of protection equipment obtained from conventional and proposed methods

| No. | Settings | OT for IP (s) | OT for Ip (s) | Settings | OT for IP (s) | OT for Ip (s) |
|-----|----------|--------------|--------------|----------|--------------|--------------|
|     | Conventional method (not considering new constraints)                        | Proposed method (considering new constraints)    |
|     | TMS/PCS/RT: 0.497/400/2          | 0.8512       | 1.2444       | TMS/PCS/RT: 0.176/920/2 | 0.8311       | 1.3370       |
| R1  | TMS/PCS/RT: 1.803/195/3          | 0.3040       | 0.6873       | TMS/PCS/RT: 1.885/210/3 | 0.3688       | 0.8343       |
| R2  | TMS/PCS/RT: 0.603/250/2          | 0.2661       | 0.8460       | TMS/PCS/RT: 1.344/250/3 | 0.3788       | 0.9614       |
| R3  | TMS/PCS/RT: 0.114/500/3          | 0.5127       | 0.3808       | TMS/PCS/RT: 0.171/500/3 | 0.2462       | 0.5730       |
| R4  | TMS/PCS/RT: 0.050/55/3           | 0.0006       | 0.0014       | TMS/PCS/RT: 0.133/190/3 | 0.0190       | 0.0460       |
| R5  | TMS/PCS/RT: 0.261/330/2          | 0.3028       | 0.4534       | TMS/PCS/RT: 0.261/330/2 | 0.3028       | 0.4534       |
| R6  | TMS/PCS/RT: 0.05/50/3            | 0.0009       | 0.0016       | TMS/PCS/RT: 0.211/200/3 | 0.0612       | 0.1093       |
| R7  | FT           | 0.0562       | 0.1059       | FT:15     | 0.2493       | 0.5736       |
| F8  | FT:4        | 0.0226       | 0.0315       | FT:13     | 0.2282       | 0.3258       |
| F9  | FT:8        | 0.0479       | 0.0874       | FT:8      | 0.0479       | 0.0873       |
| F10 | FT:13       | 0.1347       | 0.2417       | FT:13     | 0.1347       | 0.2417       |
| F11 | FT:4        | 0.0134       | 0.0249       | FT:4      | 0.0134       | 0.0249       |
| F12 | FT:12       | 0.0230       | 0.0383       | FT:12     | 0.2016       | 0.3417       |
| F13 | FT:4        | 0.0190       | 0.0343       | FT:4      | 0.0190       | 0.0343       |
| F14 | FT:4        | 0.0190       | 0.0326       | FT:4      | 0.0190       | 0.0326       |
| F15 | FT:3        | 0.0740       | 0.1243       | FT:8      | 0.0740       | 0.1243       |
| F16 | FT:3        | 0.0270       | 0.0428       | FT:8      | 0.0270       | 0.0428       |
| F17 | FT:4        | 0.0812       | 6.2071       | FT:4      | 0.0812       | 6.2071       |
| OF  | FT:4        | 0.0270       | 6.2071       | FT:4      | 0.0270       | 6.2071       |
|     | FT:18       | 0.0270       | 6.2071       | FT:4      | 0.0270       | 6.2071       |

TABLE 5  The false melting issues in conventional and proposed methods

| Reverse | Primary | Conventional method | Proposed method | Reverse | Primary | Conventional method | Proposed method | Reverse | Primary | Conventional method | Proposed method |
|---------|---------|---------------------|-----------------|---------|---------|---------------------|-----------------|---------|---------|---------------------|-----------------|
| F8      | R2      | 0.057               | 0.048           | F9      | R3      | 0.086               | 0.047           | F13     | R2      | 0.0265             | 0.060           |
|         |         | 4.085               | 0.407           |         |         | 0.555               | 4.215           |         |         | 1.999              |                 |
| R4      | 0.267   | 18.916              | 0.251           | R6      | 0.081   | 4.629               | 0.275           | R7      | 0.004   | 1.027              |                 |
| R5      | 0.430   | 19.240              | 1.804           | R6      | 0.278   | 5.530               | 0.043           | R7      | 0.0326  | 0.046              |                 |
| R6      | 0.430   | 2.160               | 4.629           | R6      | 0.430   | 5.530               | 0.043           | R7      | 0.0326  | 0.046              |                 |
| R7      | 0.832   | ∞                   | 0.030           | F9      | 0.812   | ∞                   | 0.030           | F9      | 0.832   | ∞                   |                 |
| F9      | 0.430   | 19.240              | 0.251           | F9      | 0.812   | ∞                   | 0.030           | F9      | 0.832   | ∞                   |                 |
| F10     | 0.145   | 5.492               | 0.053           | F10     | 0.145   | 5.492               | 0.053           | F10     | 0.145   | 5.492               |                 |
| F11     | 0.145   | 5.492               | 6.276           | F11     | 0.145   | 5.492               | 6.276           | F11     | 0.145   | 5.492               |                 |
| F12     | 0.491   | 47.728              | 0.700           | F12     | 0.491   | 47.728              | 0.700           | F12     | 0.491   | 47.728              |                 |
| F13     | 0.879   | ∞                   | 6.276           | F13     | 0.879   | ∞                   | 6.276           | F13     | 0.879   | ∞                   |                 |
| F14     | 0.196   | ∞                   | 26.709          | F14     | 0.196   | ∞                   | 26.709          | F14     | 0.196   | ∞                   |                 |
| F15     | 0.081   | ∞                   | 9.004           | F15     | 0.081   | ∞                   | 9.004           | F15     | 0.081   | ∞                   |                 |
| F16     | 0.043   | 4.716               | 0.902           | F16     | 0.043   | 4.716               | 0.902           | F16     | 0.043   | 4.716               |                 |
| F17     | 0.043   | 4.716               | 26.709          | F17     | 0.043   | 4.716               | 26.709          | F17     | 0.043   | 4.716               |                 |
| F18     | 0.043   | 4.716               | 26.709          | F18     | 0.043   | 4.716               | 26.709          | F18     | 0.043   | 4.716               |                 |

method encounter false fuse melting ($\Delta t = -0.030$ in Figure 8a) as well as false tripping ($\Delta t = -0.004$ in Figure 8b). However, by applying the proposed method, the false melting of F9 and the false tripping of R5 will be resolved ($\Delta t = 0.403$ in Figure 8a and $\Delta t = 1.550$ in Figure 8b).

4.2  Comparison of proposed method with methods relying on FCL

In [5–7], a method based on installing FCL has been presented to decrease the forward and reverse SCCs to acceptable ranges.
| Reverse equip. | Primary equip. | Conventional method(s) | Proposed method(s) | Reverse equip. | Primary equip. | Conventional method(s) | Proposed method(s) | Reverse equip. | Primary equip. | Conventional method(s) | Proposed method(s) |
|---------------|---------------|------------------------|-------------------|---------------|---------------|------------------------|-------------------|---------------|---------------|------------------------|-------------------|
| R2            | R3            | 0.957                  | 1.406             | R4            | R3            | 0.979                  | 1.866             | R6            | R2            | 2.058                  | 1.993             |
| R6            | 2.536         | 3.151                  |                   |               |               |                        |                   | R4            | 3.729         | 3.646                  |                   |
| R7            | 4.501         | 5.426                  |                   |               |               |                        |                   | R5            | 3.895         | 3.877                  |                   |
| F8            | 2.788         | 3.211                  |                   |               |               |                        |                   | F8            | 1.765         | 1.570                  |                   |
| F11           | 4.382         | 5.371                  |                   |               |               |                        |                   | F9            | 7.748         | 7.542                  |                   |
| F12           | 5.258         | 6.418                  |                   |               |               |                        |                   | F10           | 7.780         | 7.780                  |                   |
| F13           | 5.238         | 6.217                  |                   |               |               |                        |                   | F14           | 35.581        | 35.581                  |                   |
| F16           | 8.012         | 9.822                  |                   |               |               |                        |                   | F15           | 35.395        | 35.395                  |                   |
| F17           | 8.065         | 9.875                  |                   |               |               |                        |                   | F17           | 35.395        | 35.395                  |                   |
| F18           | 12.886        | 15.863                 |                   |               |               |                        |                   | R2            | 0.910         | 1.472                  |                   |
| R3            | R2            | 0.910                  | 1.472             |               |               |                        | R7               | R2            | 0.021         | 0.551                  |                   |
| R4            | 1.500         | 2.940                  | R5               |               |               |                        | R4               |               | 0.006         | 1.410                  |                   |
| R5            | 1.663         | 3.170                  |                   |               |               |                        | R5               |               | 0.025         | 1.885                  |                   |
| F9            | 2.304         | 5.362                  |                   |               |               |                        | F8               |               | 0.021         | 3.326                  |                   |
| F10           | 2.286         | 5.569                  |                   |               |               |                        | F9               |               | 0.007         | 3.525                  |                   |
| F14           | 3.369         | 10.146                 |                   |               |               |                        | F10              |               | 0.007         | 3.525                  |                   |
| F15           | 3.367         | 10.136                 |                   |               |               |                        | F11              |               | 0.022         | 0.551                  |                   |
| F10           | –0.003        | 1.551                  |                   |               |               |                        | F12              |               | 0.006         | 1.410                  |                   |
| F11           | –0.035        | 4.213                  |                   |               |               |                        | F13              |               | –0.003        | 1.219                  |                   |
| F12           | 0.103         | 5.393                  |                   |               |               |                        | F14              |               | 0.059         | 7.354                  |                   |
| F13           | 0.093         | 5.189                  |                   |               |               |                        | F15              |               | 0.058         | 7.344                  |                   |
| F14           | 0.059         | 3.111                  |                   |               |               |                        | F16              |               | 0.057         | 1.163                  |                   |
| F15           | 0.059         | 3.107                  |                   |               |               |                        | F17              |               | 0.002         | 1.217                  |                   |
| F16           | 0.104         | 10.894                 |                   |               |               |                        | F18              |               | 0.000         | 1.967                  |                   |
| F17           | 0.158         | 10.945                 |                   |               |               |                        |                   |               |              |                        |                   |
| F18           | 0.256         | 39.199                 |                   |               |               |                        |                   |               |              |                        |                   |

**FIGURE 8** Interference of the operation of F10 and (a) F9 and (b) R5 for SC in $\varphi_{10}$
In [7], only the relay false tripping issue is considered. The method presented in [7] utilises the minimum value of FCL impedance to solve the protection issues caused by the presence of DG such that the protection settings have the least change. In this case, four FCLs with an impedance of 154.33, 91.17, 235.34 and 220.78 Ω are installed in series with DGs. Table 7 shows the maximum reverse SCC seen by the protective equipment before and after the installation of FCLs, and the optimal settings using the method of [7] and the proposed method, respectively. The settings of the relays and fuses and the values of the OF are shown in Table 8. As can be seen, only the settings of the two relays R5 and R7 have changed. For this approach, the addition of a FCL is required and thus the capital costs are high.

In the method presented in [5], by decreasing the SCCs and observing the constraints in (22) and (23), it is shown that the false melting and the false tripping issues can be mitigated. Constraint (22) suggests that \( FT \) is selected in a way that \( PCM \) of the fuse is be larger than the maximum reverse SCC seen by the fuse. In the same way, constraint (23) suggests that \( PCS \) of NDOCR is larger than the maximum reverse SCC seen by relay.

### Table 7

IRs (in amperes) in FCL using methods and proposed method

| No. | Protection zone | Method of [7] | Method of [5] | Proposed method |
|-----|----------------|--------------|--------------|-----------------|
|     |                | Max IR | PCS or MMC | Max IR | PCS or MMC | Max IR | PCS or MMC |
| R2  | R2             | 194.9 | 195       | 374.9 | 375       | 1941 | 210       |
| R3  | R2             | 99.9  | 250       | 323.5 | 550       | 1927 | 250       |
| R4  | R2             | 74.1  | 500       | 248.9 | 275       | 1501 | 500       |
| R5  | R2             | 123.5 | 125       | 134.9 | 135       | 689  | 190       |
| R6  | R2             | 48.7  | 330       | 124.1 | 315       | 967  | 330       |
| R7  | R2             | 48.8  | 50        | 124.1 | 125       | 1011 | 200       |
| F8  | R2             | 51.9  | 75        | 207   | 336       | 1305 | 532       |
| F9  | R2             | 74.5  | 188       | 253   | 300       | 1658 | 375       |
| F10 | R2             | 52    | 75        | 209.9 | 210       | 1448 | 207       |

### Table 8

Settings of protection equipment obtained from FCL using methods and proposed method

| No. | Method of [7] | Method of [5] | Proposed method |
|-----|--------------|--------------|-----------------|
|     | TMS/PCS/RT: 0.497/400/2 | TMS/PCS/RT: 0.222/960/1 | TMS/PCS/RT: 0.176/920/2 |
| R2  | TMS/PCS/RT: 1.803/195/3 | TMS/PCS/RT: 0.399/375/3 | TMS/PCS/RT: 1.885/210/3 |
| R3  | TMS/PCS/RT: 0.603/250/2 | TMS/PCS/RT: 0.343/550/2 | TMS/PCS/RT: 1.344/250/3 |
| R4  | TMS/PCS/RT: 0.114/500/3 | TMS/PCS/RT: 0.375/275/3 | TMS/PCS/RT: 0.171/500/3 |
| R5  | TMS/PCS/RT: 0.050/125/3 | TMS/PCS/RT: 0.200/135/3 | TMS/PCS/RT: 0.133/190/3 |
| R6  | TMS/PCS/RT: 0.261/330/2 | TMS/PCS/RT: 0.683/315/3 | TMS/PCS/RT: 0.261/330/2 |
| R7  | TMS/PCS/RT: 0.050/50/3 | TMS/PCS/RT: 0.122/125/3 | TMS/PCS/RT: 0.211/200/3 |
| F8  | FT: 8         | FT: 12       | FT: 15         |
| F9  | FT: 4         | FT: 11       | FT: 13         |
| F10 | FT: 8         | FT: 10       | FT: 8          |
| F11 | FT: 13        | FT: 15       | FT: 13         |
| F12 | FT: 4         | FT: 8        | FT: 4          |
| F13 | FT: 4         | FT: 9        | FT: 12         |
| F14 | FT: 4         | FT: 6        | FT: 4          |
| F15 | FT: 4         | FT: 6        | FT: 4          |
| F16 | FT: 8         | FT: 12       | FT: 8          |
| F17 | FT: 4         | FT: 8        | FT: 4          |
| F18 | FT: 4         | FT: 9        | FT: 4          |
| OF  | 8.8532        | 11.5164      | 7.5560         |
| ΣZ_{fd} | 701.6273 (Ω) | 272.7025 (Ω) | 0              |
for fuse: \[ \max(I_{R_f}) < MMC_f \] \hspace{1cm} (22)

for relay: \[ \max(I_{R_r}) < PCS_r \] \hspace{1cm} (23)

The optimization problem is solved using the hybrid GA and linear programming (LP) method presented in [5]. Since the establishment of constraints (22) and (23) is not possible without limiting the injected SCC of DGs (reverse SCCs of equipment), four FCLs with impedances of 44.74, 83.17, 91.12 and 53.68 Ω are installed in series with the DGs. The result shows that the size of FCLs obtained from the method of [5] are lower than that of the method of [7]. Table 7 shows the reverse SCC in the protective equipment after the FCL installation as presented in [5]. According to Table 8, OF of FCL method is larger than that of the proposed method and it means that the sensitivity of the protection system will be reduced by installing FCL. On the other hand, the proposed method may avoid the false melting and the false tripping issues without installation of FCL, and has an OF that is lower than that of the FCL method. Therefore, the sensitivity of the protection system using the settings of the proposed method will be greater than that of the FCL method.

Figures 9 and 10 show how the false melting of F13 and the false tripping of R7 for maximum three-phase SC in \( \Omega_{04} \) are solved using the proposed method and FCL method,
respectively. The FCL method prevents the false melting and the false tripping issues by selecting $M_{MC}$ of F13 and $R_{CS}$ of R7 to be greater than their maximum reverse SCCs, and decreasing the maximum reverse SCC of F13 and R4, respectively, from 846 to 188 A (Figure 9) and from 628 to 80 A (Figure 10) by FCLs. However, it is obvious that the proposed method prevents the false melting and the false tripping issues only by correction of the equipment’s settings and without any changes in SCCs. Therefore, the proposed method from the cost perspective and implementation capability is better than the FCL method.

4.3 Solving the proposed coordination problem using intelligent optimization algorithms

The proposed coordination problem with OF as (8b) and optimization constraints as (8b–8g) can be solved by intelligent optimization algorithms. Table 9 lists the OF and simulation time (ST) by solving the proposed coordination problem using the firefly algorithm (FA), PSO, SOS, BBO, cuckoo search algorithm (CSA), grey wolf optimization (GWO), imperialist competitive algorithm (ICA), GA, and teaching learning-based optimization (TLBO). It is concluded that the MILP approach reaches the minimum OF with less computational time. Therefore, this result shows the superiority of the proposed method based on MILP for solving the coordination problem.

4.4 The comparison of the proposed method with previous methods

The comparison of the conventional method, the FCL methods [5] and [7] and the proposed method using GA and MILP can be seen in Table 10. According to Table 10, although the OF of the conventional method is less than other methods, there are several relay false trips and fuse false blowing issues using the conventional method with both GA and MILP. Using the FCL methods can eliminate the protection problems caused by DG but with high capital costs due to FCL installation (methods of [5] and [7]). The result shows that, the proposed method solves the relay false trip and fuse false blowing issues without the need for new equipment. Due to the reduction of SCC in using FCL methods, the OF in these methods has increased. Intelligent methods based on iteration have a much higher computational time than mathematical methods such as MILP. Also, the value of the OF in the MILP method is less than the other methods.

4.5 The effect of increasing DG penetration on the proposed method

The DG penetration for the network under study has been selected in such a way that 40% of the loads can be fed by four SDGs with capacities of 6, 3, 4 and 5 MVA. However, additional case studies have been conducted considering various DG penetration levels and the results are listed in Table 11. As can be seen, as long as the DG penetration is less than 75%, the proposed method performs effectively, but at higher DG penetration levels, the proposed method has some limitation in maintaining proper protection coordination. In such a case, the combination of the proposed method and the method of using FCL can be an effective solution as seen in Table 11 for systems with significantly high penetration levels.

TABLE 9 OF and ST of proposed coordination method using intelligent optimization algorithms and MILP

| Optimization algorithms | OF  | ST (s) | Optimization algorithms | OF  | ST (s) |
|-------------------------|-----|--------|-------------------------|-----|--------|
| FA                      | 11.640 | 248    | GWO                    | 9.135 | 199    |
| PSO                     | 9.852 | 511    | ICA                    | 8.982 | 372    |
| SOS                     | 9.381 | 697    | GA                     | 8.911 | 341    |
| BBO                     | 9.244 | 204    | TLBO                   | 8.391 | 418    |
| CSA                     | 9.170 | 317    | MILP                   | 7.556 | 6.84   |

It is worthy to note that the computational time is also dependent on the system size as well as the number of protective relays and thus the proposed MILP method could be an effective approach for large-scale systems.

TABLE 10 The comparison of the conventional method, the FCL using methods [5,7] and the proposed method using intelligent optimization algorithms and MILP

|                        | Conventional method | Using FCL | Proposed method |
|------------------------|---------------------|-----------|-----------------|
|                        | GA                  | MILP      | Method [7](iterative) | Method [5](GA-LP) | Artificial intelligence(GA) | MILP |
| Number of miss-coordination | 0                   | 0         | 0               | 0               | 0                             | 0    |
| Number of relay false trip | 11                  | 13        | 0               | 0               | 0                             | 0    |
| Number of fuse false blowing | 11                  | 11        | 0               | 0               | 0                             | 0    |
| OF                     | 6.526               | 6.207     | 8.853           | 11.516          | 8.911                         | 7.556 |
| New equipment cost     | No cost             | No cost   | High cost       | Medium cost     | No cost                       | No cost |
| Analysis time (s)      | 204                 | 0.26      | 181             | 307             | 341                           | 6.84  |
TABLE 11 Settings of protection equipment obtained from FCL using method and proposed method in various DG penetration

| DG's capacity changes | Proposed method | Method of [5] | Combination of proposed and FCL method | Method of [5] | Combination of proposed and FCL method |
|-----------------------|----------------|--------------|---------------------------------------|--------------|---------------------------------------|
| +25%                  | TMS/PCS/RT:R1 0.8039/400/3 0.6236/520/3 0.6236/520/3 0.2222/960/1 0.6236/520/3 0.2304/1000/1 1.0302/400/3 | Method of [5] | Combination of proposed and FCL method |
|                       | TMS/PCS/RT:R2 1.9362/225/3 1.7812/255/3 1.8670/270/3 0.3838/375/3 1.8888/270/3 0.4078/375/3 1.8430/270/3 | Method of [5] | Combination of proposed and FCL method |
|                       | TMS/PCS/RT:R3 0.7577/350/3 0.1253/1000/3 0.1253/1000/3 0.3618/275/3 0.3343/500/3 0.3728/287.5/3 0.3343/500/3 | Method of [5] | Combination of proposed and FCL method |
|                       | TMS/PCS/RT:R5 0.1873/200/3 0.3376/200/3 0.4265/200/3 0.2317/135/3 0.5163/200/3 0.2073/135/3 0.2537/200/3 | Method of [5] | Combination of proposed and FCL method |
|                       | TMS/PCS/RT:R7 0.3254/200/3 0.5779/200/3 0.6650/200/3 0.0759/125/3 0.4885/190/3 0.0950/125/3 0.2387/200/3 | Method of [5] | Combination of proposed and FCL method |
| FT: F8               | 16 17 17 17 12 17 13 16 | Method of [5] | Combination of proposed and FCL method |
| FT: F9               | 14 15 16 16 10 16 11 16 | Method of [5] | Combination of proposed and FCL method |
| FT: F10              | 8 8 9 10 9 11 11 9 | Method of [5] | Combination of proposed and FCL method |
| FT: F11              | 13 13 13 15 13 13 13 13 | Method of [5] | Combination of proposed and FCL method |
| FT: F12              | 4 4 4 4 7 4 8 4 | Method of [5] | Combination of proposed and FCL method |
| FT: F13              | 13 14 15 9 15 8 13 13 | Method of [5] | Combination of proposed and FCL method |
| FT: F14              | 4 4 4 6 4 6 4 4 | Method of [5] | Combination of proposed and FCL method |
| FT: F15              | 4 4 4 4 6 4 6 4 | Method of [5] | Combination of proposed and FCL method |
| FT: F16              | 8 8 8 13 8 12 8 8 | Method of [5] | Combination of proposed and FCL method |
| FT: F17              | 4 4 4 8 4 8 4 4 | Method of [5] | Combination of proposed and FCL method |
| FT: F18              | 4 4 4 8 4 8 4 4 | Method of [5] | Combination of proposed and FCL method |
| OF (s)               | 8.0138 9.8534 10.0106 11.6388 9.5335 13.1290 8.9435 | Method of [5] | Combination of proposed and FCL method |
| ∑Zfcl (Ω)           | 0 0 0 49.54+89.6 0+98.1+84.1 115+154.9+170.6+115 0+8.8+10+5.2 | Method of [5] | Combination of proposed and FCL method |
| ∑Nfcl               | 0 0 0 4 1 4 3 | Method of [5] | Combination of proposed and FCL method |

5 | CONCLUSION

Here, a method for coordination of NDOCRs and fuses in active distribution networks has been proposed by considering new constraints and using optimization algorithm. The proposed method resolves the two major problems of protection systems of these networks: false tripping of NDOCRs and false melting of fuses caused by reverse SCCs injected by DGs. In the proposed method there is no need to replace available protection equipment in the distribution networks (NDOCR and fuse) with directional overcurrent relays (DOCRs), or installation of FCLs on DGs. Also the new coordination method has been formulated based on the MILP approach as a mathematical method. As shown in Table 9, the analysis time of the proposed MILP method is significantly lower than heuristic methods. Also the optimal results of solving the proposed optimization problem by the MILP are better than the results of solving the same problem with other optimization algorithms. The efficiency of the proposed MILP method is better than the intelligent algorithm in the face of more complex optimization problems. The proposed method has been applied to a real active distribution network, and the results illustrate the efficiency of the proposed method in solving false tripping of NDOCRs and false melting of fuses in comparison to previous methods. The results (Table 10) show that the proposed method based on MILP obtains the setting of protective devices with the lower OF and the lower analysis time on comparison with the previous methods. Also, this method mitigates false trip of NDOCRs and false blowing of fuses without the need for investment and installing new equipment. It is worthy to note that this method may have some limitations in networks with high DG size which can be solved by combining the proposed method with the FCL using method.

REFERENCES

1. Conti, S.: Analysis of distribution network protection issues in presence of dispersed generation. Electr. Power Sys. Res. 79, 49–56 (2009)
2. Chen, J., et al.: Penetration level optimization for DG considering reliable action of relay protection device constrains. In: Proceedings of the International Conference on Sustainable Power Generation and Supply, pp. 1–5 (2009)
3. Yazdanpanahi, H., Xu, W., Li, Y.W.: A novel fault current control scheme to reduce synchronous DG’s impact on protection coordination. IEEE Trans. Power Deliv. 29(2), 542–551 (2014)
4. Salem, M.M., et al.: Modified inverter control of distributed generation for enhanced relaying coordination in distribution networks. IEEE Trans. Power Deliv. 32(1), 78–87 (2017)

5. Chabanloo, R.M., et al.: Comprehensive coordination of radial distribution network protection in the presence of synchronous distributed generation using fault current limiter. Int. J. Electr. Power Energy Syst. 99, 214–224 (2018)

6. Elmirawy, A., Gouda, E., El-Saadany, S.: Restoring recloser-fuse coordination by optimal fault current limiters planning in DG-integrated distribution systems. Int. J. Electr. Power Energy Syst. 77, 9–18 (2016)

7. Ibrahim, D.K., et al.: New coordination approach to minimize the number of re-adjusted relays when adding DGs in interconnected power systems with a minimum value of fault current limiter. Int. J. Electr. Power Energy Syst. 85, 32–41 (2017)

8. Alam, M.N.: Adaptive protection coordination scheme using numerical directional overcurrent relays. IEEE Trans. Ind. Inf. 15(1), 64–73 (2019)

9. Shih, M.Y., et al.: Adaptive directional overcurrent coordination in the presence of distributed generation in smart grids. IEEE Trans. Ind. Appl. 53(6), S217–S228 (2017)

10. Nikolaidis, V.C., Papanikolau, E., Safigani, A.S.: A communication-assisted overcurrent protection scheme for radial distribution systems with distributed generation. IEEE Trans Smart Grid 7(1), 114–123 (2016)

11. Saleh, K.A., et al.: Optimal coordination of directional overcurrent relays using a new time-current-voltage characteristic. IEEE Trans Power Deliv. 30(2), 537–544 (2015)

12. Saleh, K.A., El-Moursi, M.S., Zeineldin, H.H.: A new protection scheme considering fault ride through requirements for transmission level interconnected wind parks. IEEE Trans. Ind. Inf. 11(6), 1324–1333 (2015)

13. Albasri, F.A., Alroomi, A.R., Talaq, J.H.: Optimal coordination of directional overcurrent relays considering fault current due to the operation of remote side relay. Electr. Power Syst. Res. 175, 105921 (2019)

14. Yazdaninejadi, A., Nazarpour, D., Talavat, V.: Optimal coordination of dual-setting directional over-current relays in multi-source meshed active distribution networks considering transient stability. IET Gener. Transm. Distrib. 13(4), 485–494 (2019)

15. Ghotbi-Maleki, M., Chabanloo, R.M.: Adaptive directional overcurrent relays coordination by invasive weed optimization. Electr. Power Syst. Res. 157, 44–58 (2018)

16. Mohammadzadeh, N., Chabanloo, R.M., Ghotbi-Maleki, M.: Optimal coordination of directional overcurrent relays considering fault current due to the operation of remote side relay. Electr. Power Syst. Res. 175, 105921 (2019)

17. Ghotbi-Maleki, M., et al.: Determination of optimal breakpoint set of overcurrent relays using modified depth-first search and mixed-integer linear programming. IET Gener. Transm. Distrib. 14(23), 5607–5616 (2020)

18. Ghotbi-Maleki, M., et al.: Online coordination of directional overcurrent relays using binary integer programming. Electr. Power Syst. Res. 127, 118–125 (2015)

19. Papapilotopoulos, V.A., Korres, G.N., Maratos, N.G.: A novel quadratically constrained quadratic programming method for optimal coordination of directional overcurrent relays. IEEE Trans. Power Deliv. 32(1), 3–10 (2017)

20. Ghotbi-Maleki, M., et al.: Protection of electricity distribution networks, 3rd edition. The Institution of Engineering and Technology (2011)

21. Ghotbi-Maleki, M., et al.: Coordination of non-directional overcurrent relays and fuses in active distribution networks considering reverse short-circuit currents of DGs. IET Gener. Transm. Distrib. 1–15 (2021). https://doi.org/10.1049/gtd2.12197