A hybrid method for recloser and sectionalizer placement in distribution networks considering protection coordination, fault type and equipment malfunction

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Abstract
An effective way to improve distribution system reliability is to place switches and protective equipment in the optimal location. Commonly, in the placement problem, the use of equipment in the designated location is assumed to be possible. But in practice, to establish protection coordination between the equipment, it is necessary to remove or relocate some of the equipment. This paper aims to increase distribution companies’ profits and reduce customer interruption costs through a feasible solution. A new hybrid method for equipment placement has been proposed that simultaneously solves the protection coordination problem. While determining the optimal number and location of reclosers and sectionalizers, the proposed method ensures protection coordination between equipment (new and existing devices). Furthermore, to achieve a more realistic and accurate model, factors such as equipment malfunction, fault types (transient and permanent), and the relationship between these faults have been carefully considered to formulate the proposed method. In this method, to solve the optimization problems related to equipment placement and protection coordination, genetic algorithm, and linear programming in MATLAB software have been used, respectively. A real-life distribution network has been utilized to evaluate the proposed method, and the results show the capability and robustness of this method.

1 | INTRODUCTION

Improving system reliability and customer satisfaction have always been one of the most important challenges in electric distribution networks. The use of protective equipment and switching device is one way to achieve this. On the other hand, improving system reliability is associated with increased investment and operating costs, and therefore there must be trade-offs between improving system reliability and costs [1, 2].

Approximately 80% of faults in distribution networks are transient faults that can be resolved by reclosing operations to prevent outages for customers [3]. In addition, in the event of permanent faults, the use of sectionalizers alongside the reclosers means that the distribution network gets divided into multiple zones so that minimal outage for the load points is provided. Also since the sectionalizers lack time–current characteristics and are easily compatible with other protective equipment such as breakers, reclosers, and fuses, sectionalizing switches can be used in the distribution network [4].

Several methods have been proposed in the literature to address the placement of switching and protective devices. For example, particle swarm [5], ant colony [6, 7], mixed integer linear programming (MILP) [2] and [8–12], genetic algorithm (GA) [13, 14], mixed-integer non-linear programming (MINLP) [15, 16], non-dominated sorting genetic algorithm (NSGA-II) [13, 14] and [17] have been used.

In [7], the simultaneous placement of reclosers and sectionalizers in a radial distribution network has been investigated. The equipment cost and customer expected outage cost (according to the customer types) are considered. A hybrid reliability index, including weighted SAIFI and SAIDI values for their target
values, has also been used to optimally place the recloser in a distributed generation (DG)-enhanced distribution network [18]. Elsewhere, the remotely controlled sectionalizer placement problem concerning customer interruption cost (CIC) and the cost of purchasing, installing, and maintaining the equipment has been resolved [8]. In contrast, a further study [11] took this into account and proposed a similar approach to locate fault indicators and sectionalizers. A multi-objective programming-based method to optimize the location of reclosers and switches has also been proposed to minimize reliability indices (SAIFI and SAIDI). The overall cost of equipment is considered simultaneously [14]. Meanwhile, considering the customers’ interruption cost and the costs related to sectionalizers and protective equipment, a method based on value-based reliability has been proposed to locate manual and automatic sectionalizers and protective equipment optimally. In this method, to evaluate the reliability more accurately, a probability distribution cost model has been developed. [15]. The reclosers and switches placement problem to improve system reliability and reduce costs has been addressed by considering uncertainties using the point estimate method (PEM) [19]. Furthermore, to place sectionalizers and improve system reliability, the re-location of existing equipment and network operating constraints (in the presence of distributed generation resources) in the event of a fault, an approach with a fuzzy membership function has been used to handle such multiple objectives [14].

As mentioned earlier, transient and permanent faults may occur in a typical distribution network. Therefore, both of these faults must be considered to perform system and customer reliability calculations to place switches and protective devices. Various studies have considered both types of faults [9, 10] and [14, 15]. The optimal placement of sectionalizers in a distribution network with large numbers of DGs which can operate in island mode has been investigated [9]. The optimal number, type, and location of equipment, including breakers, reclosers, sectionalizers, and fault indicators, have also been studied [10]. The optimal location of the existing equipment in the network is also discussed. This study considers the outage cost of consumers/producers when a variety of interruptions occurs, as well as conventional reliability indicators and the cost of equipment and crew. However, none of the above studies provides a clear link between transient and permanent faults. While a permanent fault occurring in a branch of the network may have the same effect as a transient fault for a particular load point or vice versa (as described in Section 4.4).

The protection scheme used in the network (obtained from the location problem) can be used in practice and improves the system’s reliability when it is possible to establish protection coordination between all equipment. This requirement is ignored in the studies mentioned above. To optimal placement of protection and control devices in an active distribution network, a multi-objective optimization method has been proposed that considers the coordination and selectivity of protective devices [17]. The objective functions in this method include costs and a network continuity index. A subsequent study used the placement of protective devices in an active distribution network, including breakers, reclosers, sectionalizers, fuses, and isolating switches, to improve system reliability and provide automatic restoration through the deployment of intentional islanding or alternate feeders while considering protection coordination [21]. However, while examining the role of protection coordination in solving placement problems, these latter two studies assumed that all equipment is functioning properly, whereas the improper performance of the equipment will affect the efficiency of the protection scheme and the reliability of the system. While both studies considered transient and permanent faults, no relationship between these faults was established. In subsequent sections of this paper, their direct impact on placement problems is explained.

In this paper, to improve the system’s reliability and increase the profits of distribution companies and reduce customer interruption costs, the problem of determining the number and optimal location of reclosers and sectionalizers has been solved while considering the shortcomings mentioned above. Therefore, a hybrid method is proposed in this paper that simultaneously with the placement problem, solves the protection coordination problem so that it is possible to use the equipment at the designated location in practice. Also to achieve a more realistic model and more accurate evaluation of system reliability, equipment performance and fault types are included in the formulation of the proposed method. Besides that, to solve the placement and protection coordination problems, genetic algorithm and linear programming in MATLAB software have been used, respectively. A real-life 183-bus distribution network has been used to evaluate the robustness of the proposed hybrid method. The main contributions of this paper are as follows:

(i) In the formulation of the proposed hybrid method, the protection coordination problem is solved simultaneously with the placement problem to achieve feasible solutions. While achieving the optimal number and location of equipment, this method also ensures the establishment of protection coordination between the equipment. Therefore, the answer to the problem of placement is feasible in practice, and there is no need to relocate and remove or add equipment to achieve protection coordination, which saves time and money. Also, technical constraints and constraints related to protection coordination are included in solving placement and protective coordination problems.

(ii) The probability of equipment malfunction, which affects both the reliability calculations and the protection coordination between the equipment, is considered in all the possible cases in the proposed hybrid method’s formulation. Also the fault types (transient and permanent) and the relationship between them are included in the problem formulation and in examining all cases related to equipment malfunction.

The paper’s remainder is organized as follows: Section 3 deals with the problem definition, and Section 4 fully describes the proposed hybrid method. Section 5 shows the numerical results.
and related discussions. Finally, the conclusion is provided in Section 6.

2 | PROBLEM DEFINITION

When faults occur in distribution networks, the proper and timely operation of protection and switching devices can ensure the restoration of service to load points and the network’s return to the normal state. So having the right number of switching devices in the right places can help improve system reliability. But this is not the whole story. A protection scheme, including protective and switching devices, is valid only when its components coordinate with one another. For example, consider the hypothetical distribution network in Figure 1. This protection scheme can be used in practice if the following conditions are met:

(i) The instantaneous and delayed operation time of the recloser is shorter than the breaker's fast and delayed operation time (assuming the capability to perform reclosing operations).

(ii) The fuse’s minimum melting time must be greater than the instantaneous operation time of the recloser, and the maximum clearing time of the fuse must be smaller than the delayed operation time of the recloser (the fuse at the load side) [4].

(iii) Assuming four functions for the recloser, sectionalizers S1 and S2 operate with the recloser’s second operation if the counting mechanism is activated. Also, S3 operates with the recloser’s third operation (where the recloser’s first and fourth operations are specific to its instantaneous operation and lockout, respectively). So the maximum number of sectionalizers that can be placed downstream of the recloser is 2. For example, in the hypothetical distribution network in Figure 1, it is impossible to place sectionalizers in branches B3, B4, and B5 simultaneously.

(iv) Only one protective device can be placed on each branch.

The cases mentioned above consider the feasibility of protection coordination in the protection scheme in Figure 1. The next step is the proper and timely operation of the equipment. Suppose a permanent fault occurs in branch B5. In such circumstances, the recloser R1 first performs a reclosing operation (instantaneous operation). Since the fault is not transient, the fault current will not be interrupted. With the second recloser operation, sectionalizer S2, whose counting mechanism was activated, operates, and opens. In this case, the load points L2, L3, L4, L8, L9, L10, and L11 will experience transient outage (due to the reclosing operation), and load points L5, L6, and L7 are faced with power outage until the repair operation is completed. Finally, the load point L1 will experience no outage. Now, if S2 does not perform well after the second recloser operation, the fault current is still fed and, with the third recloser operation, sectionalizer S3 operates and opens. So, in addition to load points L5, L6, and L7, load points L3 and L4 are faced with power outages until the repair operation is completed. Therefore, the probability of equipment malfunction can impact reliability calculations.

Now consider the occurrence of a permanent fault in the B4 branch. In this case, with the third function of R1, sectionalizer S1 operates and opens, and then the disconnection command is sent to S2 remotely (RST). The connection command is then sent to remote-type manoeuvre switch NO1, and the service restoration time to the load points L5, L6, and L7 are RST+RST. Suppose NO1 does not work properly for any reason (such as a failure to send the command remotely or connect the manoeuvre switch). In that case, the manoeuvre operation must be performed manually (MST). In this case, the manual-type manoeuvre switch NO2 must be connected, and the service restoration time to the load points L5, L6, and L7 are RST+RST+MST. This example illustrates the impact of equipment malfunction on the service restoration time to the load points.

On the other hand, the protection scheme employed should perform well in both permanent and transient faults. Suppose that the transient fault occurs in branch B1 of the hypothetical network in Figure 1. In this case, if the reclosing operation is not performed upstream of branch B1 for any reason (such as the inability to reclose at the breaker or a malfunction in reclosing operations), the transient fault in this branch will cause the permanent outage of all load points. Now, suppose a permanent fault occurs in branch B6, in which case, load points L3, L4, L8, L9, L10, and L11 are subject to transient outage due to reclosing operations (first and second recloser operation). During this time, the sectionalizer S3 operates and interrupt fault current, and load points L5, L6, and L7 will face permanent outages. The above examples clearly illustrate the impact of protection coordination, equipment malfunction, fault types, and the relationship between these faults on the feasibility of applying protection schemes and improving system reliability. Therefore, to achieve a realistic and practical protection scheme, it is necessary to consider the above factors’ impact when installing protective equipment and switching devices.

3 | PROPOSED HYBRID METHOD

In this paper, to achieve a feasible solution for determining the number and optimal location of reclosers and sectionalizers, a
hybrid method has been proposed that has different objective functions and constraints that need to be further discussed.

3.1 Placement problem objective function

The presence of switching and protection devices in distribution networks ensures a reduction in the number and duration of outages for customers and improves the system’s reliability. On the other hand, the cost of purchasing, installing, and maintaining equipment is significant. Therefore, the placement of reclosers and sectionalizers is an optimization problem, and a compromise must be made between improving the reliability of the system (taking into account the interests of distribution companies and customers) and costs. The objective function used to determine the optimal number and location of reclosers and sectionalizers is shown in Equation (1) [8, 19]:

\[
\text{Maximize } f = R_E + R_f - C_{I\!N\!V} - C_M
\]

\[
R_E = \sum_{i=1}^{N_i} (E\!N\!S_i - E\!N\!S_2) \times C_E \times (1 + L_C)^{-1} \times (1 + i_t)^{-i_t}
\]

\[
R_f = \sum_{i=1}^{N_i} (I\!C_{i,1} - I\!C_{i,2}) \times (1 + L_C)^{-1} \times (1 + i_t)^{-i_t}
\]

\[
C_{I\!N\!V} = N_{rec} \times \text{COST}_{rec} + N_{fuses} \times \text{COST}_{fuses}
\]

\[
C_M = \sum_{i=1}^{N_i} C_{I\!N\!V} \times \left( \frac{C_{mp}}{100} \right) \times (1 + i_t)^{-i_t}
\]

The method for calculating the energy not supplied (E\!N\!S) and C\!I\!C\! is described in the following. Equations (6)–(8) are used to calculate the E\!N\!S of the system [20]:

\[
U_{i,j} = \lambda_{i,j} r_{i,j}
\]

\[
U_{i,j} = \sum_{j=1}^{N_{j}} U_{i,j}
\]

\[
E\!N\!S = \sum_{j=1}^{N_{j}} L_{i,j} U_{i,j}
\]

According to the average C\!I\!C\! curve [22], the interruption cost for different types of customers (residential, commercial, and industrial) is estimated as a polynomial function of the outage time, shown in Equations (9)–(11).

\[
IC_{rec} (t_U) = -0.0004715 t_U^4 + 0.00185 t_U^3 + 0.0003597 t_U^2 + 1.926 t_U + 0.01752
\]

\[
IC_{ind} (t_U) = -0.1725 t_U^4 + 1.38 t_U^3 - 1.247 t_U^2 + 3.747 t_U + 4.004
\]

Also the total interruption cost (TIC) of customers is calculated as follows:

\[
\text{CIC}_{i,j} = \lambda_{i,j} IC_{i,j} L_{i,j}
\]

\[
\text{TIC} = \sum_{j=1}^{N_{j}} \sum_{i=1}^{N_{i}} \text{CIC}_{i,j}
\]

3.2 Technical constraint

This study assumes a breaker in the main network (branch 1) and fuses are available in some lateral branches whose location is predetermined.

(i) Branch 1 is the circuit breaker’s location and is not considered a candidate location for installing a recloser and sectionalizer.

(ii) In each branch, only one number of switching or protective device can be placed.

(iii) The performance of the sectionalizer depends on the presence and performance of the recloser. Therefore, the placement of the sectionalizer in a branch is allowed when there is a recloser upstream of that branch.

(iv) In this study, a maximum of four functions for the recloser are considered, and therefore the maximum number of series sectionalizers that can be placed downstream of a recloser is 2.

(v) The locations of fuses and their downstream branches are not candidates for the installation of reclosers and sectionalizers.

3.3 Protection coordination problem

The protection scheme (obtained from placement problem) used in a network is valid when the equipment coordinates with each other and operates in the shortest possible time. For this purpose, this paper introduces Equation (14) as the objective function for the protection coordination problem. It is used to achieve the optimum configuration of protective equipment to operate in the shortest possible time. Furthermore, the coordination constraint for the overcurrent relays, fuses, reclosers, and sectionalizers has been presented in [4]. It should be noted that this paper assumes that the location of fuses is predetermined and that fuses are no longer used as backup fuses. Therefore,
fuse-fuse coordination is not considered.

\[ \text{minimize } OF = \sum_k NPD_k \cdot t_k \]  

(14)

The operation times of reclosers and overcurrent relays are also obtained from Equation (15). But since the type and location of the fuses present in the network are predetermined, their minimum melting time and total clearing time are also predetermined and are equal to the fixed numbers.

\[ OT_{PD} = \left( \frac{A_{PD}}{M_{PD}}^{P-1} + B_{PD} \right) \times TSM_{PD}, \quad M = \frac{I_{SC,PD}}{I_{P,PD}}, \quad TSM_{PD} = \left( \frac{14 \times n - 5}{9} \right) \]  

(15)

According to the conditions mentioned above, the decision variables are the time setting and pickup current of the reclosers and relays (breakers), where the latter cause the problem to be non-linear. In the proposed hybrid method, the protection coordination problem is solved for each answer to the placement problem to ensure its feasibility. So, the non-linearity of the protection coordination problem extends the program’s run time. Now, suppose constant values replace the pickup currents of the relays and reclosers. In that case, the relays and reclosers’ operation time is obtained from Equation (18), and the protection coordination problem becomes a linear problem so that the time required to solve it is sharply reduced. In this study, to increase the reliability of the results obtained from the protection coordination problem, the problem is investigated for four different numbers (4 steps) in the range mentioned in Equation (16). The flowchart for solving the protection coordination problem is shown in Figure 2.

\[ OT_{PD} = \left( \frac{A_{PD}}{M_{PD}}^{P-1} + B_{PD} \right) \times TSM_{PD}, \quad M = \frac{I_{SC,PD}}{I_{P,PD}} \]  

(18)
3.4 | Relationship between transient and permanent faults

This paper considers both transient and permanent faults in the placement problem, so it is necessary to pay attention to these faults’ relationship. For this purpose, a transient outage rate coefficient \((TORC)\) and permanent outage rate coefficient \((PORC)\) matrix are introduced. In these matrices, the number of rows is equal to the number of network branches, and the number of columns is equal to the network load point. Further explanation is given below.

The \(TORC\) matrix elements are binary and can have two values of either 0 or 1:

(i) If \(TORC(i,j) = 0\), this indicates that the \(i\)th branch’s transient fault causes a transient outage at the \(j\)th load point.

(ii) If \(TORC(i,j) = 1\), this means that the reclosing operation is not performed upstream of the \(i\)th branch, the branch’s transient fault effects such as a permanent fault on the \(j\)th load point.

\(PORC\) matrix elements are also binary:

(i) If \(PORC(i,j) = 0\), this means that the permanent fault occurring in the \(i\)th branch preserves its permanent nature at the \(j\)th load point (causing a permanent outage in the \(j\)th load point).

(ii) If \(PORC(i,j) = 1\), this means that the permanent fault occurring in the \(i\)th branch causes a transient outage in the \(j\)th load point. This situation occurs when \(r_{ij} = 0\), and \(\lambda_{p,i,j} \neq 0\). In other words, there is no recloser in the common path. It should be noted that the path mentioned in Equation (3) in [19], in this paper is called the common path, corresponding to the load point and branch where the permanent fault occurred, but there is an isolator switch (sectionalizer or fuse) that is open when the recloser is open upstream of the common path. Since the isolation operation is performed automatically, the amount of time spent on isolating the faulty segment can be neglected and has the same effect as a transient fault on the load point.

3.5 | Correction and calculation of final values of transient and permanent fault rates

In the previous section, \(TORC\) and \(PORC\) matrices were introduced. How they affect the modified, and final amounts of the transient and permanent outage rates can now be examined. Equations (19) and (20) represent the interaction of transient and permanent faults:

\[
\lambda_{r,i,j}^{\text{modified}} = (1 - TORC(i,j)) \times \lambda_{t,i,j} + PORC(i,j) \times \lambda_{p,i,j}
\]

\[
\lambda_{p,i,j}^{\text{modified}} = (1 - PORC(i,j)) \times \lambda_{p,i,j} + TORC(i,j) \times \lambda_{t,i,j}
\]

3.6 | Effect of equipment malfunction on system reliability

So far, it has been assumed that the network equipment gives a reliable and appropriate performance, and the reliability calculations were made based on the proper performance of the equipment. However, these devices are also subject to improper performance, which reduces their ability to improve system reliability. This section investigates the impact of improper equipment performance on system reliability and thus on the placement problem.

It should be noted that, since the reclosers and sectionalizers used in this study are remotely controllable, two types of malfunction of this equipment are possible:

(i) Failure of isolation (disconnection) or connection capability

(ii) Failure of remote-control capability

Besides, it is assumed that no more than one device will malfunction; also, of the two malfunction cases mentioned above, only one can occur at a particular time.

Before describing the various situations that may occur, it is necessary to discuss the types of malfunctions of the network’s equipment. The first device to operate after a fault is the fault current interruption (FCI) device (breaker or recloser), and its potential for malfunctioning (FCI-m) should be taken into account. In the next step, if needed, the isolation device (breaker, recloser, or sectionalizer) isolates the fault segment from the rest of the circuit. Therefore, the probabilities of isolation capability malfunction (ISO-m) and remote-control capability malfunction (ISO, R-m) in this equipment must be taken into account. The next step is to perform the restore operation in the shortest possible time and for the maximum load points available on the network. The restoration operation is performed using manual or remote manoeuvre switches. So the restoration capability malfunction (RES-m) and remote-control capability malfunction (RES, R-m) of remote-type manoeuvre switches should be considered.

3.6.1 | Investigation of the effect of the equipment malfunction during transient faults

In the event of a transient fault in one branch of the network, and depending on the location of the reclosers, three situations may occur for a particular load point:

(i) If there is a recloser in the common path, the transient outage rate will be zero.

(ii) The absence of a recloser in the common path will result in a transient outage at the load point.

(iii) In the absence of a reclosing switch (recloser or circuit breaker capable of reclosing) located upstream of the faulty branch, the transient fault becomes permanent.

So the reclosing operation is essential when a transient fault occurs. Therefore, the number of reclosing devices in each path
(the common path of the faulty branch and one particular load point) and the number of them upstream of the faulty branch can be determinative. Suppose more than one reclosing device is in these paths, and the primary protective device is malfunctioning. In that case, backup equipment acts as needed and prevents transient outages in the load points or prevents transient faults from becoming permanent.

In this paper, there is a possibility of improper operation of only one switching or protective device at a particular time. So it is assumed that when one device is malfunctioning, all other equipments will function properly.

Now, if a transient fault occurs in the \( n \)-th branch of a hypothetical distribution network, one of the following three states may occur at the \( n \)-th load point:

First state: There is more than one reclosing switch in the common path:

\[
\lambda^{FC_{-m}}_{i,i,j} = 0
\]  

(21)

Second state: There is no recloser in the common path, and more than one recloser upstream of the faulty branch. Or there is one recloser in the common path and at least one recloser upstream of the faulty branch:

\[
\lambda^{FC_{-m}}_{i,i,j} = \lambda_{i,j}
\]  

(22)

Third state: There is a maximum of one recloser in total in the common path and upstream of the faulty branch.

\[
TORC^{FC_{-m}}_{i,j} = 1
\]  

(23)

3.6.2 Investigation of the effect of device malfunction when a permanent fault occurs

So far, it has become clear that when a permanent fault occurs in a branch of the network (\( n \)-th branch), for one particular load point (\( n \)-th load point) depending on the location of the protective device (recloser, sectionalizer, and fuse), the following three situations may occur:

(i) The load point does not experience a permanent outage. In this case, the load point is not downstream of the faulty branch, and there is a fault current interruption switch in the common path between the load point and the faulty branch. The load point will not be interrupted if this switch is functioning properly.

(ii) It is possible to restore service to the load point via the manoeuvre switches; In this case, the load point is downstream of the faulty branch, and it is possible to use the manoeuvre switches.

(iii) The load point faces a power outage until the repair operation is completed. In this case, the load point is downstream of the faulty branch, and the conditions for using the manoeuvre switches are not met.

In general, an equipment malfunction during a permanent fault in the \( n \)-th branch of a hypothetical network will meet one of the conditions listed in Table 1 for the \( j \)-th load point.

\[
\lambda^{FC_{-m}}_{p,i,j} = 0
\]  

(24)

\[
\lambda^{FC_{-m}}_{p,i,j} = 0
\]  

(25)

\[
TORC^{FC_{-m}}_{i,j} = 1
\]  

(26)

\[
\lambda^{ISO,R_{-m}}_{p,i,j} = \lambda_{p,i}
\]  

(27)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST
\]  

(28)

\[
\lambda^{ISO,R_{-m}}_{p,i,j} = \lambda_{p,i}
\]  

(29)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + MST
\]  

(30)

\[
\lambda^{ISO,R_{-m}}_{p,i,j} = \lambda_{p,i}
\]  

(31)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + RST
\]  

(32)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(33)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + MST + RST
\]  

(34)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + MST + MST
\]  

(35)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + RST
\]  

(36)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(37)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(38)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(39)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(40)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(41)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(42)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(43)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(44)

\[
r^{ISO,R_{-m}}_{p,i,j} = RST + RST + MST
\]  

(45)
### Table 1: Different states in the case of equipment malfunction when permanent fault occurs

| State number | Position and number of switches | Relevant equations |
|--------------|----------------------------------|-------------------|
| 1            | Existence of more than one protective device in the common path | Backup device is a recloser (24) and (25) |
|              |                                   | Backup device is not a recloser (25) and (26) |
| 2            | There is only one protective device in the common path | Manoeuvre switch is remote type (27) and (29) |
| 3            | It is possible to use the manoeuvre switches, and there is more than one protective device upstream of the fault branch, while the fault current interruption device is malfunctioning | Manoeuvre switch is manual type (27) and (30) |
| 4            | It is possible to use the manoeuvre switches, and the protective device upstream of the faulty branch works well, but the fault isolator switch’s remote-control capability is malfunctioning | In the path of the load point to the fault branch, there is another fault isolator switch (31) and (32) |
|              |                                   | The manoeuvre switch is remote type (31) and (33) |
|              |                                   | The manoeuvre switch is manual type (31) and (33) |
|              |                                   | There is only one fault isolator switch between the load point and the faulty branch (31) and (34) |
|              |                                   | The manoeuvre switch is remote type (31) and (35) |
|              |                                   | The manoeuvre switch is manual type (31) and (35) |
| 5            | It is possible to use the manoeuvre switches where the upstream protective device of the faulty branch has good performance, and remote control of the fault isolator switch is successfully performed, but due to malfunction, it is not possible to open the line with this switch | In the path of the load point to the faulty branch, there is another fault isolator switch (36) and (37) |
|              |                                   | The manoeuvre switch is remote type (36) and (38) |
|              |                                   | The manoeuvre switch is manual type (36) and (39) |
|              |                                   | There is only one fault isolator switch between the load point and the faulty branch (36) and (39) |
|              |                                   | The manoeuvre switch is remote type (36) and (39) |
|              |                                   | The manoeuvre switch is manual type (36) and (39) |
| 6            | Remote-type manoeuvre switches are used where the fault current interruption device and fault isolator switch operate correctly, but the manoeuvre switch’s remote-control capability is malfunctioning | It is possible to use another remote manoeuvre switch (40) and (41) |
|              |                                   | There is no other remote manoeuvre switch that can be used (40) and (42) |
| 7            | Remote-type manoeuvre switches are used where the fault current interruption device and fault isolator switch operate correctly, and the remote control of the manoeuvre switch is successfully applied, but due to malfunctioning, the manoeuvre switch cannot be connected | It is possible to use another remote manoeuvre switch (43) and (44) |
|              |                                   | There is no other remote manoeuvre switch available for use, but a manual-type manoeuvre switch is available (43) and (45) |
|              |                                   | There is no other manoeuvre switch to use (43) and (46) |
|              |                                   | Other manoeuvre switches are available (43) and (47) |
| 8            | Manual-type manoeuvre switches are used where the fault current interruption device and fault isolator switch operate correctly, but the manoeuvre switch cannot be connected due to malfunctioning | There is no other manoeuvre switch available for use (43) and (46) |

\[
\begin{align*}
T^{RES-m}_{p_i,j} & = r_{p_i} \quad (46) \\
T^{RES-m}_{p_i,j} & = RST + MST + MST \quad (47)
\end{align*}

### 3.7 Correction and calculation of the U matrix in terms of equipment malfunction

Among the parameters that affect the value of \(RE\), only \(ENS\) changes for different cases. The previous sections described how to calculate or modify \(ENS\), \(r\), and \(\lambda\) (transient and permanent) in different conditions. Now, to calculate and modify the \(U\) matrix, in case of equipment malfunction when a permanent fault occurs, Equations \((53)–(55)\) are expressed. Due to the short duration of the transient faults (taking into account the modified values of \(\lambda\)), these types of faults are not considered in calculating the unavailability of load points.

In order to simplify the expression of equations, Equations \((48)–(52)\) are first presented:

\[
\begin{align*}
U^{FCI-m}_{i,j} & = \lambda^{FCI-m}_{p_i} \times T^{FCI-m}_{p_i,j} \\
U^{ISO,R-m}_{i,j} & = \lambda^{ISO,R-m}_{p_i} \times T^{ISO,R-m}_{p_i,j} \\
U^{ISO-m}_{i,j} & = \lambda^{ISO-m}_{p_i} \times T^{ISO-m}_{p_i,j} \\
U^{RES,R-m}_{i,j} & = \lambda^{RES,R-m}_{p_i} \times T^{RES,R-m}_{p_i,j} \\
U^{RES-m}_{i,j} & = \lambda^{RES-m}_{p_i} \times T^{RES-m}_{p_i,j}
\end{align*}
\]
Before expressing the different states that may occur, it is necessary to pay particular attention to the equipment’s sequence of operation. In fact, the performance of some equipment depends on the performance of others (cascading mode). Also if there is no need to use a device, its performance, or the possibility of its malfunction will not be considered.

First state: In this state, during a permanent fault of the \( i \)th branch and depending on its position relative to the \( j \)th load point, the only device that operates is the fault current interruption switch. Therefore, the probability of its malfunctioning should also be considered.

\[
U_{i,j}^{\text{modified}} = p_{\text{fun}}^{\text{IC}} U_{i,j} + \left(1 - p_{\text{fun}}^{\text{IC}}\right) U_{i,j}^{\text{IC} - m} \tag{53}
\]

Second state: In this state, when a permanent fault occurs in the \( i \)th branch and depending on its position relative to the \( j \)th load point, it is possible to use manoeuvre switches to restore service to the load point. Therefore, the fault current interruption switch, fault isolator, and manoeuvre switches are all in operation, and their potential for malfunctioning must be taken into account. If the manoeuvre switch used in this case is manual, Equation (54) is applicable:

\[
U_{i,j}^{\text{modified}} = p_{\text{fun}}^{\text{IC}} p_{\text{fun}}^{\text{SO} - R} p_{\text{fun}}^{\text{SO} - m} p_{\text{fun}}^{\text{RES} - m} U_{i,j} + \left(1 - p_{\text{fun}}^{\text{IC}}\right) U_{i,j}^{\text{IC} - m} + p_{\text{fun}}^{\text{IC}} \left(1 - p_{\text{fun}}^{\text{SO} - R}\right) U_{i,j}^{\text{SO} - m, R} + p_{\text{fun}}^{\text{IC}} p_{\text{fun}}^{\text{SO} - R} \left(1 - p_{\text{fun}}^{\text{SO} - m}\right) U_{i,j}^{\text{SO} - m} + p_{\text{fun}}^{\text{IC}} p_{\text{fun}}^{\text{SO} - R} p_{\text{fun}}^{\text{RES} - m} \left(1 - p_{\text{fun}}^{\text{RES} - m}\right) U_{i,j}^{\text{RES} - m} \tag{54}
\]

Third state: This state is the same as the previous state, except that the manoeuvre switch used in this case is remotely controlled. So Equation (55) is now applicable:

\[
U_{i,j}^{\text{modified}} = p_{\text{fun}}^{\text{IC}} p_{\text{fun}}^{\text{SO} - R} p_{\text{fun}}^{\text{SO} - m} p_{\text{fun}}^{\text{RES} - m} U_{i,j} + \left(1 - p_{\text{fun}}^{\text{IC}}\right) U_{i,j}^{\text{IC} - m} + p_{\text{fun}}^{\text{IC}} \left(1 - p_{\text{fun}}^{\text{SO} - R}\right) U_{i,j}^{\text{SO} - m, R} + p_{\text{fun}}^{\text{IC}} p_{\text{fun}}^{\text{SO} - R} \left(1 - p_{\text{fun}}^{\text{SO} - m}\right) U_{i,j}^{\text{SO} - m} + p_{\text{fun}}^{\text{IC}} p_{\text{fun}}^{\text{SO} - R} p_{\text{fun}}^{\text{RES} - m} \left(1 - p_{\text{fun}}^{\text{RES} - m}\right) U_{i,j}^{\text{RES} - m} \tag{55}
\]

The set of Equations (53)–(55) expresses changes in load points’ unavailability for different states, which affect EN5, RE, and ultimately the objective function.

### 3.8 Correction and calculation of CIC matrix in terms of equipment malfunction

#### 3.8.1 Correction and calculation of CIC matrix in terms of equipment malfunction during a transient fault

When transient faults occur, only the function of the reclosing devices is important. Therefore, in this case, only the function (proper performance or malfunction) of these switches will be considered in calculating the CIC matrix. On the other hand, due to the negligible duration of transient faults, the parameter “\( P \)” in the set of Equations (9)–(11) will be approximately equal to zero. Therefore, the interruption cost (\( IC \)) will be equal to a fixed number, depending on the customer type. Therefore, to calculate the \( CIC_{ij} \) (each element of the matrix) of the system CIC, Equation (56) is used:

\[
CIC_{i,i,j}^{\text{modified}} = L_j \left[ \lambda_{i,i,j} IC_{i,i,j} + \left(1 - p_{\text{fun}}^{\text{IC}}\right) \lambda_{i,i,j}^{\text{IC} - m} IC_{i,i,j} \right] \tag{56}
\]

It should be noted that in Equation (56), the values corresponding to the outage rate (\( \lambda \)) are the corrected and final values taking into account the interrelationship between transient and permanent faults.

#### 3.8.2 Correction and calculation of CIC matrix in terms of equipment malfunction during a permanent fault

In the event of a permanent fault, the operation of all equipment can be important. Also depending on the faulty branch position and the location of various types of protective equipment, different situations may occur for a particular load point. Therefore, according to the equipment’s necessity and order of performance, the system’s CIC matrix is determined as discussed below. But before that, to simplify the expression of equations, Equations (57)–(62) are presented:

\[
IC_{p,i,j} = IC \left( r_{p,i,j} \right) \tag{57}
\]

\[
CIC_{p,i,j}^{\text{IC} - m} = IC \left( r_{p,i,j}^{\text{IC} - m} \right) \tag{58}
\]

\[
CIC_{p,i,j}^{\text{SO} - R - m} = IC \left( r_{p,i,j}^{\text{SO} - R - m} \right) \tag{59}
\]

\[
CIC_{p,i,j}^{\text{SO} - m} = IC \left( r_{p,i,j}^{\text{SO} - m} \right) \tag{60}
\]

\[
CIC_{p,i,j}^{\text{RES} - R - m} = IC \left( r_{p,i,j}^{\text{RES} - R - m} \right) \tag{61}
\]

\[
CIC_{p,i,j}^{\text{RES} - m} = IC \left( r_{p,i,j}^{\text{RES} - m} \right) \tag{62}
\]

Among the parameters that affect the value of \( R_i \), only TIC changes for different cases. On the other hand, TIC is related to CIC and IC matrices, according to Equations (12) and (13). The purpose of this section is to illustrate how to calculate and correct \( CIC_{ij} \) when the equipment fails to function properly. It should be noted that, because transient and permanent faults are different in nature, these two types of faults are considered separately.
First state: In this case, when a permanent fault occurs in the \(i\)th branch and depending on its position relative to the \(j\)th load point, the only equipment that operates is the fault current interruption switch. Therefore, the probability of its malfunctioning should be considered. So, Equation (63) is used:

\[
CIC_{\text{modifed}}^{\text{first}} = L_{n,i} \left[ p_{\text{fun}}^{\text{CIC}} \lambda_{p,i,j} I_{C,i,j} + \left( 1 - p_{\text{fun}}^{\text{CIC}} \right) \lambda_{p,i,j} I_{C,j} \right] 
\]

(63)

Second state: In this case, a permanent fault occurs in the \(i\)th branch. Depending on its position relative to the \(j\)th load point, the fault current interruption device, fault isolator switch, and manoeuvre switch are operating. Therefore, the probability of these devices malfunctioning should be considered. Now, if the manoeuvre switch used in this case is manual, Equation (64) is applicable:

\[
CIC_{\text{modifed}}^{\text{second}} = L_{n,i} \left[ p_{\text{fun}}^{\text{CIC}} p_{\text{fun}}^{\text{ISO-R}} p_{\text{fun}}^{\text{RES}} \lambda_{p,i,j} I_{C,i,j} + \left( 1 - p_{\text{fun}}^{\text{CIC}} \right) p_{\text{fun}}^{\text{ISO-R}} p_{\text{fun}}^{\text{RES}} \lambda_{p,i,j} I_{C,j} + \left( 1 - p_{\text{fun}}^{\text{CIC}} \right) p_{\text{fun}}^{\text{ISO}} \lambda_{p,i,j} I_{C,j} \right] 
\]

(64)

Third state: This case is the same as the previous state, except that the manoeuvre switch used in this case is remote-type. Therefore, Equation (65) is now applicable:

\[
CIC_{\text{modifed}}^{\text{third}} = L_{n,i} \left[ p_{\text{fun}}^{\text{CIC}} p_{\text{fun}}^{\text{ISO-R}} p_{\text{fun}}^{\text{RES}} \lambda_{p,i,j} I_{C,i,j} + \left( 1 - p_{\text{fun}}^{\text{CIC}} \right) p_{\text{fun}}^{\text{ISO-R}} p_{\text{fun}}^{\text{RES}} \lambda_{p,i,j} I_{C,j} + \left( 1 - p_{\text{fun}}^{\text{CIC}} \right) p_{\text{fun}}^{\text{ISO}} \lambda_{p,i,j} I_{C,j} \right] 
\]

(65)

The set of Equations (63)–(65) expresses changes in the interruption cost of load points for different states, which affect \(CIC, TIC, RI\), and ultimately objective function.

### 3.9 Genetic algorithm

In this paper, a genetic algorithm is used to solve the placement problem. A chromosome is produced to use the initial population consisting of two rows. The first row is for reclosers, the second row for sectionalizers, and the number of columns equal to the number of branches in the network (Figure 3). To generate an initial population in the genetic algorithm, each of the chromosome genes can assign one of the binary numbers 0 and 1. Thus, the numbers 0 and 1 represent the existence or absence of equipment in the corresponding branch, respectively.

But this is not the whole story, and to generate the initial population as well as the crossover and mutation operations, the technical constraints stated earlier in Section 4.2 must be considered.

The flowchart of the proposed hybrid method for solving the optimization problem is shown in Figure 4.

### 4 NUMERICAL RESULTS

To validate the proposed hybrid method, a real-life distribution system in Simorgh County, Iran, is used. The test network single-line diagrams are presented in Figure 5. The values of network parameters, fuses’ location and operating time, and manoeuvre switches’ types and locations in the network are given in Tables 7, 8, and 9 in the appendix. Also the location of the breaker is the first branch of the test network.

The proposed hybrid method is implemented in the following two case studies on the network shown in Figure 5, and the results are presented in Tables 3–6. But before that, the base case study is introduced.

### 4.1 Base case study

In this case, the only protection equipment available in the network is the breaker in the overhead distribution network and the fuses in the lateral branches listed in Table 8 in the Appendix. It should be noted that, for the naming of the branch number in the test network, Equation (66) is used:

\[
\text{Branch number} = \text{Branch receiver bus number} - 1 \quad (66)
\]

The values of \(ENS, ENS\ cost,\) and \(CIC\) for the base case study during the operational period (for five years) are given in Table 2.

### 4.2 First case study

In this case study, the placement problem without considering protection coordination between the protective device has been investigated in two states:

- Assuming the proper operation of all equipment (case study 1-1)
- Considering the possibility of equipment malfunction (case study 1-2)
The results of this case study are presented in Tables 3 and 4. It should be noted that the probability of proper operation of the equipment and the probability of remote control of the equipment (if it has this capability) is assumed to be 0.98.

4.3 Second case study

In this case study, the placement problem for the proposed test system is investigated concerning the protection coordination between the protective device in two states:

- Assuming proper operation of all available network equipment (case study 2-1)
- Considering the probability of equipment malfunction (case study 2-2)

The results of this case study are given in Tables 5 and 6.

4.4 Investigation of the effect of equipment malfunction on the test system

It is sufficient to compare the two case studies 1-1 and 1-2 to investigate the effect of equipment malfunction on the placement problem in the test network. The difference is in terms of the possibility of equipment malfunction.

According to Table 4, it can be seen that as expected, the value of the objective function in case study 1-2 has decreased by more than US $8,000 compared to case study 1-1. Table 3 also shows that the number and location of reclosers and sectionalizers in these two case studies are slightly different. In other words, although about 19 candidate locations for the installation of reclosers are the same in these two case studies, but there are significant differences between them, which can be
carefully examined to determine the impact of equipment malfunction in the placement problem. As shown in Table 3, the number of reclosers increased in case study 1-2 compared to case study 1-1, but the number of sectionalizers decreased. Also branches 13, 24 and 108, which were proposed in case study 1-1 for the installation of sectionalizers, are candidates for installing reclosers in case study 1-2. The main reason for this difference is the sectionalizer performance’s dependence on the upstream recloser performance, which becomes more apparent when the equipment is malfunctioning. The following is an example to illustrate this point:

Suppose in case study 1-1; a permanent fault occurs in branch number 109. In this case, the sectionalizer in branch 108 operates with the second recloser function in branch 102 and opens the line. As a result, the three load points downstream of this sectionalizer will experience service outages. If the recloser in branch 102 cannot interrupt the fault current due to malfunction, the backup recloser in branch 9 will take effect. Therefore, the sectionalizer in branch 13 also operates with the second reclosing function in branch 9 and opens the line. The result of this unintended action will be an outage for 95 load points (about 73% of the total network load points), which is very different from the previous conditions. But in case study 1-2, there would be no such problem by replacing the recloser with these sectionalizers and placing equipment in more convenient locations. Therefore, the impact of the possibility of equipment malfunction will be much less.

TABLE 4  Distribution company profit, CIC reduction and objective function value in the first case study

|                      | Case study 1-1 | Case study 1-2 |
|----------------------|----------------|----------------|
| Distribution company profit due to reduction in energy not supplied ($) | 63,503,1654 | 62,935,9586 |
| Amount of reduction in customer interruption cost due to reduction in interruption cost ($) | 3,826,702,8032 | 3,810,071,0154 |
| Objective function value ($) | 3,637,576,9294 | 3,629,022,1352 |
TABLE 5  Number and location of reclosers and sectionalizers in the second case study

| Device name | Device's number | Case study 2-1 | Case study 2-2 | Device's location (branch number) |
|-------------|----------------|---------------|---------------|----------------------------------|
| Recloser    | 18             | 18            |               | 3, 6, 12, 21, 33, 49, 59, 73, 78, 83, 97, 102, 108, 115, 121, 126, 132, 141 |
| Sectionalizer| 11             | 13            |               | 9, 17, 26, 38, 44, 64, 68, 100, 118, 123, 153 |

TABLE 6  Distribution company profit, CIC reduction and objective function value in the second case study

| Case study | Case study 2-1 | Case study 2-2 |
|------------|----------------|----------------|
| Distribution company profit due to reduction in energy not supplied ($) | 63,217,6235 | 63,040,9451 |
| Amount of reduction in customer interruption cost due to reduction in interruption cost ($) | 3,653,490.0577 | 3,635,379.1549 |
| Objective function value ($) | 3,502,845.6629 | 3,475,150.9550 |

4.5  Investigation of the effect of protection coordination on the test system

It has already been stated that the solution obtained by solving the placement problem is feasible and can be used in practice when it is possible to establish protection coordination between the equipment (new and existing devices). In this regard, this paper proposes a hybrid method to achieve this goal. It is sufficient to compare case studies 1-2 and 2-2 to prove this claim because the only difference between them is the consideration of protection coordination in the placement problem.

According to Tables 3 and 5, it can be easily seen that in case study 2-2 compared to case study 1-2, the number of reclosers meaningfully decreased, while the number of sectionalizers increased significantly. With more attention, it can be seen that the ten branches, including 13, 17, 64, 68, 97, 100, 102, 108, 118 and 123, which mainly are branches with long length and high failure rate) that were proposed in case study 1-2 of the installation of the recloser, in case study 2-2 to establish protection coordination are the candidate locations for installing sectionalizers. In addition to clearly showing the effect of establishing protection coordination on the placement problem, this issue indicates the advantage of using sectionalizers in the protection scheme. Because, these types of equipment do not have time–current characteristics and can easily coordinate the performance with other equipment (recloser, fuse etc.). Also only 8 and 1 branches of candidate locations for installation of recloser and sectionalizer, respectively, are the same in these two case studies. Therefore, the answer to the placement problem in these two case studies is completely different.

Besides, Tables 4 and 6 show that considering protection coordination, the objective function’s value has decreased by more than US $150,000 in case study 2-2 compared to case study 1-1.

5  CONCLUSION

This paper presents a hybrid method that, while determining the optimal number and location of reclosers and sectionalizers, ensures protection coordination between equipment. The effectiveness of the proposed method has been evaluated by applying it to a real-life distribution network. The results indicate the need to pay attention to protection coordination to use the equipment at the designated location in practice. In this way, considering the protection coordination, the equipment’s optimal number and location undergo many changes. While improving the reliability of the system, it is possible to establish protection coordination between the equipment. Also to achieve a more accurate model, the possibility of equipment malfunction has been considered in the problem formulation. The results also show that considering the possibility of equipment malfunction, changes are made in the optimal number and location of reclosers and sectionalizers to make equipment more economical and functional. The proposed method also proves that depending on the fault location, fault types, the position of the load points, and the equipment’s location, there is a possibility of changing the fault’s nature (transient fault becoming permanent or vice versa) for a particular load point. Therefore, the relationship between transient and permanent faults has been carefully studied and considered in the placement problem. Finally, the impact of distributed generation resources on the proposed method can be considered as a future research area.

NOMENCLATURE

Indices and sets

\( i, N_{br} \)  Index and set of branches
\( j, N_{l} \)  Index and sets of load points
\( k, N_{PD} \)  Index and set of protective devices
\( t, N_{s} \)  Index and set of years

Parameters and constants

\( ENS_{i} \)  Energy not supplied \((ENS)\) of the system in the base case
\( C_{E} \)  Present cost of each unit of energy
**Functions and variables**

| Symbol | Description |
|--------|-------------|
| $L_C$  | Annual rate of load growth in percentage |
| $i_r$  | Annual rate of interest in percentage |
| $TIC_1$ | $TIC$ of the system in the base case |
| COST$_{rec}$ | Cost of a recloser |
| COST$_{sec}$ | Cost of a sectionalizer |
| $C_{cap}$ | Cost of maintenance in percentage of total recloser and sectionalizer cost |
| $\lambda_{Z,i,j}$ | Failure rate of $i$th load point due to failure of $j$th branch ($Z$: $p$, $t$ where $p$ and $t$ are permanent and transient faults respectively) |
| $r_{p,i,j}$ | Repair time of $i$th load point due to permanent failure of $j$th branch |
| $I_{m,i,j}$ | Average load in $i$th load point |
| $A_{PD}, B_{PD}$ | Constants that vary with the type of characteristic |
| $I_{SC,i,j}$ | Short circuit current passing through the protective device |
| $k_m$ | Coefficient between 1.2 and 2 |
| $\alpha_{Z,i}$ | Failure rate of $i$th branch ($Z$: $p$, $t$ where $p$ and $t$ are permanent and transient faults respectively) |
| $rp_{i,j}$ | Repair time of $i$th branch due to permanent fault |
| $RST$ | Remote switching time |
| $MST$ | Manual switching time |
| $P_{funt}^X$ | Probability of proper functionality of equipment ($X$: ‘FCI’, ‘ISO,R’, ‘ISO’, ‘RES,R’, ‘RES’) |

**REFERENCES**

1. Javadian, S.A.M., et al.: Adaptive centralized protection scheme for distribution systems with DG using risk analysis for protective devices placement. Int. J. Electr. Power Energy Syst. 44(1), 337–345 (2013)
2. Farajollahi, M., Fotuhi-Firuzabad, M., Safdarian, A.: Optimal placement of sectionalizing switch considering switch malfunction probability. IEEE Trans. Smart Grid 10(1), 403–413 (2019)
3. Sahoo, N.C., Ganguly, S., Das, D.: Multi-objective planning of electrical distribution systems incorporating sectionalizing switches and tie-lines using particle swarm optimization. Swarm Evol. Comput. 3, 15–32 (2012)
4. Gers, J.M., Holmes, E.J.: Protection of electricity distribution networks. 3rd edition The Institution of Engineering and Technology, 2011
5. Moradi, A., Fotuhi-Firuzabad, M.: Optimal switching placement in distribution systems using trinary particle swarm optimization algorithm. IEEE Trans. Power Delivery 23(1), 271–279 (2008)
6. Wang, L.W.L., Singh, C.: Reliability-constrained optimal placement of reclosers and distributed generators in distribution networks using ant colony system algorithm. IEEE Trans. Power Delivery 30(3), 1401–1409 (2015)
7. Falaghi, H., Haghifam, M.R., Singh, C.: Application of ant colony optimization method for placement of sectionalizing switches in distribution networks using a fuzzy multiobjective approach. IEEE Trans. Power Delivery 24(1), 268–276 (2009)
8. Abiri-Jahromi, A., et al.: Optimized sectionalizing switch placement strategy in distribution systems. IEEE Trans. Power Delivery 27(1), 362–370 (2012)
9. Heidari, A., Agelidis, V.G., Kia, M.: Considerations of sectionalizing switches in distribution networks with distributed generation. IEEE Trans. Power Delivery 30(3), 1401–1409 (2015)
10. Popović Brbaklić, B., Knezević, S.: A mixed integer linear programming based approach for optimal placement of different types of automation devices in distribution networks. Electr. Power Syst. Res. 148, 136–146 (2017)
11. Farajollahi, M., Fotuhi-Firuzabad, M., Safdarian, A.: Simultaneous placement of fault indicator and sectionalizing switch in distribution networks. IEEE Trans. Smart Grid 10(2), 2278–2287 (2019)
12. Lei, S., Wang, J., Hou, Y.: Remote-controlled switch allocation enabling prompt restoration of distribution systems. IEEE Trans. Power Syst. 33(3), 3129–3142 (2018)
13. Velasquez, M.A., Quijano, N., Cadena, A.I.: Optimal placement of switches on DG enhanced feeders with short circuit constraints. Electr. Power Syst. Res. 141, 221–232 (2016)
14. Pombo, A.V., Murta-Pina, J., Pires, V.F.: Multiobjective planning of distribution networks incorporating switches and protective devices using a memetic optimization. Reliab. Eng. Syst. Saf. 136, 101–108 (2015)
15. Heidari, A., Agelidis, V.G., Kia, M., et al.: Reliability optimization of automated distribution networks with probability customer interruption cost model in the presence of DG units. IEEE Trans. Smart Grid 8(1), 305–315 (2017)
16. Heidari, A., et al.: Mixed-integer nonlinear programming formulation for distribution networks reliability optimization. IEEE Trans. Ind. Inf. 14(5), 1952–1961 (2018)
17. Pereira, K., et al.: A multi-objective optimization technique to develop protection systems of distribution networks with distributed generation. IEEE Trans. Power Syst. 33(6), 7064–7075 (2018)
18. Pregelj, A., Begović, M., Rohatgi, A.: Recloser allocation for improved reliability of DG-enhanced distribution networks. IEEE Trans. Power Syst. 21(3), 1442–1449 (2006)
19. Alam, A., Pant, V., Das, B.: Switch and recloser placement in distribution system considering uncertainties in loads, failure rates and repair rates. Electr. Power Syst. Res. 140, 619–630 (2016)
20. Billinton, R., Allan, R.N.: Reliability Evaluation of Power Systems. Plenum Publishing Corp, New York (1984)
21. Lwin, M., et al.: Protective device and switch allocation for reliability optimization with distributed generators. IEEE Trans. Sustainable Energy 10(1), 449–458 (2019)
22. Brown, R.E.: Electric Power Distribution Reliability. CRC Press, (2017)

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**APPENDICES**

Tables 7 and 8 respectively show the values of the test network’s parameters and the locations of the fuses in the test network and their operation times. Table 9 also shows the types and locations of the manoeuvre switches in the test network.

### TABLE 7 Values of test network parameters

| Parameter | Value |
|-----------|-------|
| N<sub>f</sub> | 5 (years) |
| C<sub>E</sub> | 0.16 (US $ per kWh) |
| L<sub>C</sub> | 5 (in %) |
| i<sub>r</sub> | 10 (in %) |
| Cost<sub>rec</sub> | 6000 (US $) |
| Cost<sub>sw</sub> | 1500 (US $) |
| C<sub>cap</sub> | 2 (in %) |
| λ<sub>p</sub> | 0.08 (failure per km per year) |
| λ<sub>t</sub> | 0.2 (failure per km per year) |
| r<sub>p</sub> | 1.5 (h) |
| R<sub>ST</sub> | 0.1 (h) |
| M<sub>ST</sub> | 0.5 (h) |
| p<sub>x</sub> | 98 (in %) |

### TABLE 8 Locations of the fuses in the network and their operation time

| Fuse location (branch number) | Minimum melting time (s) | Total clearing time (s) |
|-------------------------------|--------------------------|-------------------------|
| 63                            | 0.0892                   | 0.6213                  |
| 66                            | 0.0998                   | 0.7053                  |
| 87                            | 0.1156                   | 0.8434                  |
| 125                           | 0.0725                   | 0.3522                  |
| 135                           | 0.0541                   | 0.2823                  |
| 147                           | 0.0505                   | 0.2632                  |
| 150                           | 0.0506                   | 0.2639                  |
| 154                           | 0.0524                   | 0.2744                  |
| 158                           | 0.0524                   | 0.2744                  |
| 167                           | 0.0589                   | 0.3050                  |
| 168                           | 0.0610                   | 0.3186                  |
| 176                           | 0.0658                   | 0.3441                  |

### TABLE 9 Locations and type of manoeuvre switches in the network

| Type and location of manoeuvre switches | Location | Type |
|----------------------------------------|----------|------|
| 98                                     | Remote   |      |
| 125                                    | Manual   |      |
| 171                                    | Manual   |      |