Effects of protection settings on optimal performance of reconfigurable smart distribution systems

Elham Khoshbakht | Farhad Namdari | Meysam Doostizadeh

Department of Electrical Engineering, Faculty of Engineering, Lorestan University, Khorramabad, Iran

Correspondence
Farhad Namdari, Department of Electrical Engineering, Faculty of Engineering, Lorestan University, Khorramabad, Iran. Email: Namdari.f@lu.ac.ir

Abstract
Nowadays, with increasing energy consumption in distribution networks and the demand of consumers to buy highly reliable power, it is of high importance to establish adaptation between protection and operation of the power system. Therefore, this paper analyses the effect of optimal reconfiguration of the smart distribution system in the presence of wind and solar renewable resources under fault conditions. Uncertainties of load and production of renewable resources are studied as well. In the proposed model, the optimal topology of the distribution network is obtained to minimise the system losses. Also, features of the distribution network protection systems, including constraints on the coordination and performance of the equipment, are added to the reconfiguration problem. According to linearisation, the proposed model becomes a mixed-integer linear programming. Several case studies are carried out on a modified 33-bus network using GAMS and MATLAB to show the effectiveness and robustness of the proposed model on both operational and protection coordination.

1 | INTRODUCTION

1.1 | Motivation and literature review

Considering the environmental and techno-economical benefits of DERs, the presence of these resources in the distribution system has increased. Also, various technologies and devices such as remote control switches and smart devices are applied to the DN. Accordingly, traditional distribution systems are converted to active distribution ones. However, the integration of renewable energy resources into an ADN brings many operational challenges due to their inherent variation and uncertainty. Changing the topology of the DN is one of the effective techniques to manage these uncertainties and probable failures during the system operation [1]. In this method, the system operates under normal conditions concerning the initial state of the switches, and, if necessary, the topology of the ADN may be changed by reconfiguration of the tie switches. DSR is performed to improve the operational conditions of the system while maintaining the radial structure of the network to improve the performance of the protection system, limit short circuits, and avoid problems of ring networks [2, 3]. The process of network reconfiguration is performed based on different goals in different periods such as hourly, daily, or seasonal. For example, reconfiguration of the DN to reduce losses involves changing the topology of the DN so that not only power losses are reduced in the network, but also the radial structure of the network is maintained [4]. In addition, improvement of reliability indices can be considered as the main purpose of DSR as in [2] and [5].

Since the operational constraints of the network such as voltage limits and feeder current limits must be fulfilled by the DSR problem, DSR is a non-differentiable non-linear constrained optimisation problem [6]. So, most of the DSR problems generally fall into the category of MINLP [11]. Solving large-scale DSR MINLP problems is not practically promising due to their computational complexity. Different methods have been used to solve the DSR problems, which can be divided into three general categories:

1. Heuristic methods [7–9].
2. Metaheuristic or intelligent optimisation methods [1, 10].
3. Mathematical optimisation methods [11–13].
In heuristic and intelligent optimisation methods, the radial structure of the DN is usually managed by implicitly. Although these methods require small amount of computations, they are unreliable and/or suboptimal [13]. On the other hand, mathematical formulation for the radial structure of the DN is required in mathematical optimisation methods. A few research works propose mathematical models for the radiality constraint. Gan et al. [14] introduce mixed-integer conic programming formulation for the DSR. In this method, DG and switching of the capacitors are investigated. A mixed-integer quadratic method is presented in [15] to optimise the DN topology. A linear load flow based on voltage dependency is reflected in this method. However, the load and renewable generation in DN has a degree of uncertainty, and consideration of the effects of these uncertainties in the DSR problem is necessary. Therefore, several methods based on uncertain parameters are applied in DSR to overcome these uncertainties. In [16], a stochastic mixed-integer second-order conic programming is presented for reconfiguration of a smart microgrid to maximise the profit of the system operator. A two-stage robust optimisation is introduced in [17], to cope with the uncertain parameters in the day-ahead DSR. A data-driven stochastic robust optimisation method based on the measurements of micro-phasor measurement units is proposed in [18] to solve the hourly DSR in a real-time manner. A risk-averse DSR strategy in the presence of DERs is proposed in [19], where the uncertainty of RESs is managed via the information gap decision theory.

Notwithstanding, certain characteristics of protective devices such as sensitivity, accuracy, speed, and reliability must be considered to ensure proper functionality under any network topology. Protection systems detect specified faults and limit any damage to power system equipment. Accordingly, an algorithm was proposed in [20] for designing a protection system capable of operating in several different configurations. In this algorithm, in addition to adjusting the protection relays in the substation buses and determining the nominal value of the reclosers and fuses, their proper installing location is also determined. Then, the permitted switching zone for the automation system is defined, in which the protection system will work properly. Similarly, the same algorithm is used in [21] and [22] except that the rules of coordination are predetermined.

Short-circuit computations show that by changing the network configuration, the amount of short-circuit current in the network will undergo changes that can cause problems for the network protection [23]. Therefore, by changing the topology of the system, the protection system may malfunction, and the DN faces an unprotected state or the normal operation of the network may be disrupted [24]. Given the degree of coordination between the protection elements and their proper operation, the system can be classified into two types [13]:

- A distribution system with semi-smart control, in which the setting of the protection relay can only be performed by the operator. In such cases, one of the following two methods must be used for the proper operation of the protection system after reconfiguration:
  - The network protection system should be designed in such a way that it has a correct and acceptable performance in some optimised forecasts, so when designing a protection system, instead of considering a specific configuration and topology, several selected configurations should be selected. Attention is paid to [25].
  - Changing the configuration should be done in such a way that the function of the pre-designed protection system for the initial topology is not disturbed and still has acceptable efficiency.

1.1.1 | Contribution

According to the comparison of the works done in the research background, the protection system is not reflected in the daily DSR problem. By examining the structures separately, the protection coordination of the network may be compromised. Therefore, the effects of DN reconfiguration on its protective coordination are studied in this paper to address this research gap. With this in mind, this paper tries to improve the performance of the protection system by determining the optimal topology and switching mode at different times. In this regard, a two-stage algorithm is presented for studying the reciprocal impact of network topology and protection system coordination. The first stage is to determine the optimal topology to reduce total losses of the DN and considering uncertainty of renewable generation. In the second stage, the obtained topology is assessed from the protection perspective. Accordingly, the main contributions of this paper can be summarised as follows.

(i) A two-stage algorithm is proposed to consider the protection system in daily DSR problem. The first stage is a mixed-integer linear programming model that optimally determines the DN topology while considering the renewable generation and load uncertainties. And, the second stage models the coordination of the protection devices.

(ii) The proposed model can easily be implemented on the ADNs with several degree of coordination between the protection devices such as semi-smart control and fully SDS.

1.2 | Paper organisation

The remaining of this paper is organised as follows. Section 2 describes the features of the proposed framework considering the proposed algorithm. Section 3 presents the problem formulation, including the objective function, operational constraints, and coordination. Section 4 analyses the simulation results of the proposed model on a modified 33-bus network. Finally, Section 5 concludes this study.
2 | PROPOSED FRAMEWORK

Reconfiguration in DNs to find the best switching using smart techniques is of vital issues in power distribution companies. Due to the appropriate protection coordination, limiting the grid’s short-circuit level of the grid, and the problems of interconnected grids, the operation of distribution grids is done as a radial form. Moreover, there are several disconnecting switches in the grid with significant roles in managing the grid structure to reach the optimal form [21]. In this study, we consider a 24-h horizon for daily operation, while the DSR operator determines the minimum network loss from switching for the next day based on forecasted load and variable generation estimates. The results have been analysed in the stochastic optimisation framework under various scenarios, and uncertainties due to consumption loads and renewable resources such as wind power and PV systems were examined by the Monte Carlo method. Therefore, reliability parameters, as well as parameters of the SDS protection, are modelled. A two-step model was used to implement the proposed framework. In the first step, the formulated reconfiguration problem is solved without protection constraints. Details are given in Section 2.1. In this case, only the reconfiguration of the protected system is examined. However, the switching provided for each objective function is different, so that the growth of one objective function leads to the loss of another. In the second step, the reconfiguration problem is solved about DG and renewable energies, and the obtained topology will be examined with the protection perspective. At this step, the network protection functionality is evaluated by determining the feasibility of resetting all or some of the protection relays. In case of inability to coordinate protection of network relays, an error signal is sent to the first step, and another optimal topology is identified, which certainly has a higher loss rate. The details of the repeating loop are fully described in the simulation section. Then, the total minimum operation time of all relays is reduced.

2.1 | Proposed algorithm

According to the above description and the mathematical modelling of various programming sections, this section presents the steps of implementing the proposed algorithm as follows:

Initially, basic information, including the basic structure of the network, is determined by using the data of the primary lines, specifications of system equipment, and load curves.

Then, reconfiguration is performed according to objective function (2) in GAMS software, and a set of new structures are provided. It should be noted that the set is sorted from low to high based on the solution obtained for the objective, that is, system losses, such that the first solution has the least loss, the second has the best value bigger than the previous one, and so on until the main network structure is reached. Pay attention to the network structure, including the original and the reconfigured structures; programming is performed in MATLAB to minimise the operating time of the protection relays, i.e. the objective function (11).

Based on the two responses obtained, the errors in the settings as well as the bi-directional relay settings are determined. Under these conditions, programming continues until the error is completely eliminated.

The flowchart of the proposed algorithm is illustrated in Figure 1 to indicate the implementation.

Steps. Optimisation Model Operation

The objective function used to reconfigure the network is to minimise the total system losses over the possible scenarios for loads and renewable generations as

$$\text{Min } J = \sum_{b=1}^{24} \sum_{s=1}^{N_s} \sum_{i=1}^{\Omega} \psi_i b_{i,b} r_{i,b} \left( p_{i,b}^2 + q_{i,b}^2 \right) V_{i,b}^{-2}.$$  \hspace{1cm} (1)

Note that if the bus voltages of the network are assumed close to 1 pu, i.e. $V_{i,b} \cong 1$, (1) can be rewritten as follows:

$$\text{Min } J = \sum_{b=1}^{24} \sum_{s=1}^{N_s} \sum_{i=1}^{\Omega} \psi_i b_{i,b} r_{i,b} \left( p_{i,b}^2 + q_{i,b}^2 \right).$$  \hspace{1cm} (2)

When the node injection (1 h) is equal to their estimated value, Problem (2) defines a definite model. But in situations where there is uncertainty in the system because of load or generation uncertainty, defining values can make it impossible to exploit the topology changes. This is due to the deviation of values from their nominal values and the deviation of programming constraints such as power balance. Here, $\psi_i$ takes into account as a probability scenario. The linearisation of the objective function is discussed in the Appendices.

Considering the linear load flow in the proposed model, power distribution is formulated in (3)–(8). In (3) and (4), the active and reactive input power for each bus are specified.

$$\sum_{i=1}^{N_i} \sum_{s=1}^{\Omega} \psi_i p_{i,m,b,i} - \sum_{i=1}^{N_i} \sum_{s=1}^{\Omega} \psi_i p_{i,m,b,i} = I_{p,m,b,i}.$$  \hspace{1cm} (3)

$$\sum_{i=1}^{N_i} \sum_{s=1}^{\Omega} \psi_i q_{i,m,b,i} - \sum_{i=1}^{N_i} \sum_{s=1}^{\Omega} \psi_i q_{i,m,b,i} = I_{q,m,b,i}.$$  \hspace{1cm} (4)

$$-y_{um} p_{i,m,b,i}^\text{max} \leq p_{i,m,b,i} \leq y_{um} p_{i,m,b,i}^\text{max},$$  \hspace{1cm} (5)

$$-y_{um} q_{i,m,b,i}^\text{max} \leq q_{i,m,b,i} \leq y_{um} q_{i,m,b,i}^\text{max},$$  \hspace{1cm} (6)

$$P_{i,m,b,i} = \sum_{i=1}^{N_i} \sum_{s=1}^{\Omega} \psi_i p_{i,m,b,i}.$$  \hspace{1cm} (7)
Receive input information including: network specifications, load and product resources

Network reconfiguration with the purpose of minimizing system losses (first objective function) and forming a list of proposed reconfigurations

Active reconfiguration n:

Protective compatibility check of active reconfiguration for proper protection system performance (second objective function)

Add active reconfiguration to the list of accepted structures

Have all the proposed reconfigurations been reviewed?

Add active rearrangement to list of rejected structures

Is it possible to set up protective relays with active reconfiguration?

Displays the values obtained in the two purpose functions for the list of structures

Have all the proposed reconfigurations been reviewed?

Start

n = n + 1

FIGURE 1 The flowchart of the proposed model

\[ Q_{n,s,t} = \sum_{r=1}^{N_s} \sum_{\omega \in \Omega_H} \psi_{r} Q_{nm,ks}, \]  

(8)

The amount of power injected into each bus is related to the amount of load and self-generation; the power balance equation of each bus is written as follows:

\[ L_{pr,ks} = d_{pr,ks} - P_{pr,ks} - P_{PV,ks} - P_{WT,ks}, \]  

(9)

\[ L_{qr,ks} = d_{qr,ks} - F(p_{FS}) \cdot P_{qr,ks} - F(p_{FS}) \cdot P_{PV,ks} - F(p_{FS}) \cdot P_{WT,ks}, \]  

(10)

2.2 Reconfiguration constraints

DN reconfiguration means the transformation of the network topology, which is performed by maintaining the radial structure of the network to improve the state of the system. That is, there should be no loops in a DN, and all busses must be fed by one of the neighbouring busses. The following equality constraint should be met for the network to remain radial after each reconfiguration:

\[ z_{nm,b} = 0 \quad \forall t, \forall \omega \in \Omega_H, \forall n \in \Omega_S \]  

(11)

\[ z_{nm,b} + z_{nm,b} = y_{nm} \quad \forall b, \forall \omega \in \Omega_H \]  

(12)

\[ \sum_{b, \omega \in \Omega_H} z_{nm,b} = 1 \quad \forall n \in \Omega / \Omega_S \]  

(13)

\[ z_{nm,b}, y_{nm} \in \{0, 1\} \quad \forall b, \forall \omega \in \Omega_H. \]  

(14)

2.3 Coordination of protection devices

To investigate the proper performance of the protection system under reconfiguration conditions, the objective function is to minimise the operating time of the primary and backup relays considering their performance priority [26]. In other words,
programming is performed in such a way that considering the current supply path, the setting of the series relays is done in the current transmission line. The objective function used for the protection is shown as

$$\text{Min } T = \sum_j T_j = \sum_j \frac{k \cdot \text{TMS}_j}{\left( \frac{I_j}{\text{PS}_j \cdot \text{CTR}_j} \right)^\theta} - 1. \quad (15)$$

The constraints of relay settings are specified in the following equations:

$$\text{TMS}_j \leq \text{TMS}_j \leq \text{TMS}_j \quad (16)$$

$$\text{PS}_j \leq \text{PS}_j \leq \text{PS}_j \quad (17)$$

$$\text{CTR}_j \leq \text{CTR}_j \leq \text{CTR}_j. \quad (18)$$

Constraint (19) is introduced to ensure the correct operation of the primary and backup relays from the perspective of responsiveness to the faults observed by both:

$$T'_j - T'_j \geq \text{CTR}_j. \quad (19)$$

Also, for a fault to be detected by the \(j\)th relay, the current passing through the relay should be greater than or equal to the product of \(\text{PS}_j\) and \(\text{CTR}_j\). The above terms are shown mathematically as follows:

$$I_j \geq \text{PS}_j \cdot \text{CTR}_j. \quad (20)$$

In (16), the only index related to the formation and structure of the network is the short-circuit current \((I_j)\) in each line. In the proposed model, due to the different resistance of the current transmission line in every structure, the short-circuit current for each structure after the reconfiguration relay is calculated separately. The short-circuit current for each relay is calculated as follows:

$$\begin{cases} I_j = I_{\text{base}} \cdot M \\ M = \frac{1}{1 + f} \end{cases} \quad (21)$$

The coefficient \(f\) can be defined according to the type of system and fault, as shown in Table B.1. Other information on how to obtain short-circuit current attenuation index for different fault types is available in the Appendices.

3 | SIMULATION RESULTS

The proposed algorithm is implemented on the 33-bus radial DN in Figure 2. The active and reactive load peaks are provided in [27]. The base power and voltage are 1 MW and 12.66 kV, respectively. In terms of SDS programming, the period is 24 h. The daily electricity demand and WT and PV generation are predicted in Figure 3. In this network, there are 33 closed and five open normal switches, which should be controlled in the optimisation. The proposed network includes both reactive and reactive loads [28, 29]. In the network under study, the main switch is located on bus no. 1, and the power supply is made only at this point. The DG resources are located on buses 22 and 30, two WTs are in buses 10 and 14, and a PV in bus 19. Depending on the position of the connection point and the primary switch, the switching and protection settings are specified based on the primary and backup protection for all lines. The number of proposed models has been examined in four scenarios. The programming conditions in each scenario differ in terms of freedom in the structure and number of re-adjustable...
relays. In order to demonstrate the importance of resetting the protection relays on the proper operation of the system in the event of an error, the modes studied in this paper are defined as follows. It should be noted that the default settings of the protection system are based on the base structure of the system under consideration.

3.1 Multi-scenario simulation comparisons and results analysis

In order to fully explore the impacts of protection coordination on the optimal operation of DN reconfiguration, to verify the validity and feasibility of the proposed method, simulations are carried out in three different scenarios.

- **Scenario 1**: In this case, the optimal network structure is determined based on the objective function of the first stage, and the possibility of synchronisation is determined according to the default settings of protection relays.
- **Scenario 2**: In this case, the optimal structure of the first stage, with the possibility of resetting 30% of the protection relays, is checked for the feasibility of protection coordination.
- **Scenario 3**: In this case, all protection relays have the ability to reset, and coordination is determined according to the optimal structure of the first stage.
- **Scenario 4**: In this case, by changing the optimal structure in successive iterations, the settings of protection relays for synchronisation are determined, and how the two functions change relative to each other is measured.

3.2 Setting the priority and short-circuit level

To determine the path of current flow to energise the network busses, first, the radial diagram of the existing structure is plotted and the corresponding graph is drafted. Table 1 shows optimal structures.

Considering the radial structure of the DN, the obtained graph is tree graph, based on which the current flow path to supply electricity to each bus can be determined. Given the existence of a protection relay on all lines, the short circuit in each line is calculated and the binary priority of the relays is determined relative to each other. According to the structure shown in Figure 1, the short-circuit level at the installation site of the protection relays is shown in Table 1. As it turns out, with the exception of line 1 relay, the backup relay number of each line is determined by the current path.

It is clear in Table 1 that both structures have 32 lines and the difference in the short-circuit current level has been reduced by moving away from the transformer. According to Table 1, it is clear that the maximum short-circuit level in the above network is 4140.855 A. This value can be calculated according to the transformer specifications and mains voltage. The amount of system losses in this case is equal to 207.759 kW. In this case, how to coordinate between protection relays, according to the second objective function, is shown in Table 2. According to Table 2, it is clear that the maximum operating time in the main line relay is equal to 4.2 s. It should be noted that the minimum operating time for the relay is 0.9 s. The duration of operation of the whole protection system in this case is equal to 66.6.

3.3 Scenario 1

According to the results obtained in the previous section, it can be concluded that increasing the path length of the branches increases the operating time of the main relay. Because the main relay must act in the last priority and if all other relays do not work, the whole network will be disconnected. Due to the direct relationship between path length and the amount of losses, it is clear that by changing the path and length of branches, in addition to reducing losses, the operating time of the entire system can be reduced. Therefore, in this case, the rearrangement problem for the distribution system has entered the model. The optimal structure of the system to minimise losses is shown in Figure 4.

According to Figure 4, it is clear that the flow path in the optimal structure has changed. So, the number of lines has a load change, and the direction of power transmission is reversed in a number of lines. In this situation, planning has been done to create coordination between protection relays using the optimal
TABLE 1  Short-circuit current and backup relays in basic

| Line number | Bus send | Bus receiver | Short-circuit current | Line number with backup relay | Line number | Bus send | Bus receiver | Short-circuit current | Line number with backup relay |
|-------------|----------|-------------|----------------------|--------------------------------|-------------|---------|-------------|----------------------|--------------------------------|
| 1           | 1        | 2           | 4140.855             | NaN                            | 17          | 17      | 18          | 3920.999             | 16                              |
| 2           | 2        | 3           | 4134.487             | 1                               | 18          | 2       | 19          | 4138.065             | 1                               |
| 3           | 3        | 4           | 4125.173             | 2                               | 19          | 19      | 20          | 4119.985             | 18                              |
| 4           | 4        | 5           | 4117.107             | 3                               | 20          | 20      | 21          | 4099.439             | 19                              |
| 5           | 5        | 6           | 4104.216             | 4                               | 21          | 21      | 22          | 4087.526             | 20                              |
| 6           | 6        | 7           | 4093.47              | 5                               | 22          | 3       | 23          | 4124.252             | 2                               |
| 7           | 7        | 8           | 4083.921             | 6                               | 23          | 23      | 24          | 4109.715             | 22                              |
| 8           | 8        | 9           | 4065.541             | 7                               | 24          | 24      | 25          | 4090.543             | 23                              |
| 9           | 9        | 10          | 4043.866             | 8                               | 25          | 6       | 26          | 4093.302             | 5                               |
| 10          | 10       | 11          | 4031.01              | 9                               | 26          | 26      | 27          | 4088.119             | 25                              |
| 11          | 11       | 12          | 4025.121             | 10                              | 27          | 27      | 28          | 4073.899             | 26                              |
| 12          | 12       | 13          | 4006.235             | 11                              | 28          | 28      | 29          | 4054.336             | 27                              |
| 13          | 13       | 14          | 3985.836             | 12                              | 29          | 29      | 30          | 4040.676             | 28                              |
| 14          | 14       | 15          | 3974.43              | 13                              | 30          | 30      | 31          | 4025.354             | 29                              |
| 15          | 15       | 16          | 3961.047             | 14                              | 31          | 31      | 32          | 4012.162             | 30                              |
| 16          | 16       | 17          | 3940.851             | 15                              | 32          | 32      | 33          | 4005.506             | 31                              |

TABLE 2  How to coordinate protection relays in the base structure

| Line number | Relay operation time | TMS | PS  | CTR | Line number | Relay operation time | TMS | PS  | CTR   |
|-------------|----------------------|-----|-----|-----|-------------|----------------------|-----|-----|------|
| 1           | 4.2                  | 0.786 | 1.815 | 626.419 | 17 | 1           | 0.277 | 1.191 | 491.262 |
| 2           | 4                    | 0.865 | 1.366 | 681.885 | 18 | 1.6         | 0.754 | 1.8   | 94.201  |
| 3           | 3.8                  | 0.759 | 1.657 | 626.679 | 19 | 1.4         | 0.755 | 0.5   | 216.925 |
| 4           | 3.6                  | 0.566 | 1.961 | 707.351 | 20 | 1.2         | 0.287 | 1.19  | 663.032 |
| 5           | 3.4                  | 0.84  | 1.701 | 441.119 | 21 | 1           | 0.303 | 1.265 | 405.568 |
| 6           | 3.2                  | 0.593 | 1.588 | 715.556 | 22 | 1.4         | 0.235 | 1.962 | 657.492 |
| 7           | 3                    | 0.382 | 1.689 | 1000    | 23 | 1.2         | 0.354 | 1.158 | 470.24  |
| 8           | 2.8                  | 0.613 | 1.526 | 588.678 | 24 | 1           | 0.247 | 1.503 | 498.168 |
| 9           | 2.6                  | 0.565 | 1.155 | 781.96  | 25 | 2.4         | 0.486 | 1.784 | 567.813 |
| 10          | 2.4                  | 0.601 | 1.951 | 369.373 | 26 | 2.2         | 0.602 | 1.357 | 460.237 |
| 11          | 2.2                  | 0.615 | 1.581 | 373.665 | 27 | 2           | 0.313 | 1.882 | 732.259 |
| 12          | 2                    | 0.498 | 1.949 | 370.346 | 28 | 1.8         | 0.752 | 1.363 | 173.173 |
| 13          | 1.8                  | 0.565 | 0.626 | 740.865 | 29 | 1.6         | 0.6   | 1.424 | 219.323 |
| 14          | 1.6                  | 0.543 | 1.252 | 312.454 | 30 | 1.4         | 0.517 | 0.687 | 470.774 |
| 15          | 1.4                  | 0.406 | 1.326 | 408.215 | 31 | 1.2         | 0.566 | 1.581 | 103.796 |
| 16          | 1.2                  | 0.256 | 1.464 | 616.525 | 32 | 1           | 0.256 | 1.126 | 611.838 |

structure. Figure 5 shows the best operating conditions of the protection system for the least amount of performance error. According to the figure, it is clear that in the new structure, 14 lines have no proper settings and the protection sequence is not observed to see the error in them. It should be noted that the amount of time error is shown on the above lines.

According to the direction and order of power passing through the network lines, the fault shall be distinguished by the first upstream relay and checking all the settings of the other relays.

According to Figure 5, red lines indicate inconsistency. It is clear that in the above conditions, if an error occurs on the line between buses 10 and 11, i.e. line 10, the backup relays of this line do not work properly; at this stage, an error occurs such that the relay settings are correct. So, the network sees the error and disconnects. As a result, the error is transferred to bus 21.
point, due to the faster operation of the backup relay, the line between bus 20 and 21, i.e. line 15, the error reaches line 21, the time is less and trip is given, and it is controlled. In this situation, most of the load, including buses 8, 9, 15, 16, 17, 18, and 33, is cut. For example, this interruption is not necessary because miss coordination relays have the same error. As a result, the blackout range increases.

### 3.4 Scenario 2

In this case, the possibility of coordinating the protection system with respect to resetting a number of protection relays has been investigated. In this case, the degree of inconsistency for the network under consideration is shown in Figure 6. Comparing Figures 5 and 6, it is clear that in addition to reducing the number of relays with improper performance, the amount of time error of performance has also decreased. Therefore, it can be concluded that in the second case, both of the objective functions have been improved. The problem of system rearrangement and coordination can improve the operating conditions from the perspective of each of the target functions.

The point to be made in this situation is whether the best coordination is achieved only with the optimal structure or another structure may be in better condition in terms of coordination. Therefore, in the third case, this issue has been investigated. So, the planning conditions of the third mode are implemented for different structures, and the set of answers in the solution space is specified.
3.5  |  Scenario 3

Since not all protection relays in the network can be reprogrammed in this scenario, the conditions for limiting the number of relays, with reset, are considered. In the above conditions, it may not be possible to comply with all the protection constraints for the proposed structure, and as a result, the network structure is selected from a set of predetermined optimal structures in this scenario. The above process continues until an optimal structure is compatible with the protection system.

In this case, the condition of the degree of dependence of the two functions of the target of losses and the coordination of the protection system has been investigated. It should be noted that the operating conditions in this case are the same as in the second case. The difference is that in this case, planning seeks complete coordination between the network structure and the protection system. Due to the two-stage solution of the problem and considering the two functions of loss targets and operating time of the whole system, the necessary coordination between the two functions has been created using the proposed algorithm. In the proposed algorithm, first, the best network structure is determined in the first step, loss minimisation. Then, the optimal structure is sent to the second stage to be tested for protection feasibility. At this stage, due to the level of short-circuit current intensity as well as the backup relays of different lines, the performance of the protection system has been optimised. In this case, if the model is insoluble and the time constraints of the protection relays are not observed, the error signal is sent to the first stage. Due to the insolubility of the best structure in terms of losses, in the second iteration, the level of system losses increases and is added to the main problem as a constraint. It should be noted that the amount added to the level of losses is due to the difference in system losses in the first and second cases. In this case, to re-solve the problem in the first case, the answer to the second step is sent again. The above repetition process has continued until a certain number of repetitions. Figure 5 shows the modified method of programming parameters for the list of feasible topologies of the first objective function in different structures. It is clear from Figure 7 that there are different structures with loss rates between the basic and optimum values. The planning accuracy in this article for searching different structures is equal to 100 repetitions. In order to better analyse the separate applicable responses are presented in Table 3.

The normalisation method can be used to determine the best answer. In this way, initially, the values of the two functions at the answer points are normalised according to the minimum and maximum pans. The diagram of the answer points is shown below. The optimal answer is the point that has the closest distance to the hypothetical line of the graph $y = x$. Because at this point both functions have the smallest difference with respect to their minimum value. This point is indicated in Fig. 8.

According to Table 3, only a few of the networks in the designated list are potentially adapted with protection. By plotting the solution for the two objective functions in Figure 9, the best point can be identified from the two objective functions with different weighting coefficients. As is well known, concerning the increasing order of losses to the structures, for situations where only losses are important, the first structure has the highest degree of membership. Meanwhile, the 11th coordinated structure, the 85th structure in Table 3, is better than all other structures in terms of coordination. Given the 50% importance of each function, the second coordination structure, structure 4 in Table 3, is chosen as the best structure with both loss and protection coordination.

3.6  |  Scenario 4

In this case, planning has been done according to the possibility of resetting all protection relays. Due to the above conditions, in this case, there is no more performance error among the relays due to the change in structure. The reason for this is the reprogramming of all relays according to
the new structure. The results obtained in this case are presented in Table 4. The system loss in this case is equal to 139.17 kW.

Table 4 represents the optimisation results for the second case. By comparing the two tables of 3 and 4, it is clear that the operating time of the main relay in this case is equal to 3 and has decreased by 28.57% compared to the first case. The reason for this is the reduction in the strength of the network tree branches. So, all branches have almost the same resistance. The total operating time of the system in this case is 53. Comparing the total operating time of the relays in the fourth mode with the default settings, it is clear that in the fourth mode, the system has faster performance against various errors in the network and is able to detect and disconnect faults in less time.

In this structure, the primary lines of the basic structure are used to adjust the protection relays. Also, the optimal structure for minimising system losses is shown in Table 5.

Scenario 1 is without protection settings, which shows that if the reset is without protection, it is not technically possible to coordinate the relays in many cases. Scenario 2 is to use the existing system relays unchanged, the losses are much higher than the first scenario, and we have introduced this mode as unplanned protection. Scenario 3 examines the replacement of some system relays with programmable relays that actually consider semi-intelligent protection. Reason for using Scenario 3 companies cannot change all relays at once and gradually do so only for some relays. Scenario 4 is equivalent to changing all protection relays to programmable relays, in which case the protection is completely intelligent. In this case, the possibility of online changes in settings of the relays will cause lower losses in comparison with Scenario 3 but a higher cost of changing the relays.

The results of the surveys conducted in the sample DN are as follows.

- The main problem that occurs in reconfiguration without considering the protection constraints and in most cases is related to the performance of the relays. In solving the reconfiguration without considering the protection constraints, it can be noted in several scenarios in all cases, several relays operate the network under load and cut off the load. In some cases, the mismatch of fuses with each other has disrupted the network protection system.
- Although studies have shown that short-circuit displacement depends on different configurations as well as on semi-smart and fully smart control systems that regulate the protection relays in the network, there is a possibility of disruption in the coordination of these equipments.
- Therefore, by using the proposed method, in addition to using the advantages of this method in the operation of DNs that have scattered production resources or renewable energy
production resources, the performance of the protection system can also be improved.

- The most important innovation point of this article is that it is not possible to synchronise the system if protection coordination is not considered in the reconfiguration.

### 4 Conclusion

This paper analysed the coordination of network structure with two approaches to minimising losses and reducing the operating time of protection relays. Creating a set of proper solutions, the proposed scenario was investigated in terms of loss and coordination of different DN topologies about the protection parameters. It provides a restructuring or a group of optimal topologies for the losses in such a way to coordinate their protection. The results of simulation showed that in addition to the importance of coordinated loss and protection programming, fine-tuning of control parameters using actual short-circuit current at each point prevents the malfunction of the protection system. It was also found that separately examining each of the objective functions can lead to a local optimal response. Sensitivity analysis of the number of reconfigurable relays revealed that by increasing the number of relays, a better running time could be achieved and TMS could be minimised. The optimal network topology determined in Scenario 1 (based on the objective function of the first stage) was problematic, while the system losses reduced from Scenario 2 to Scenario 4, and the number of miss coordination decreased.

### Abbreviations

| Abbreviation | Definition               |
|--------------|--------------------------|
| AND          | Active distribution network. |
| DERs         | Distributed energy resources. |
| DG           | Distributed generation. |
| DN           | Distribution network. |
| DSR          | Distribution system reconfiguration. |
| MINLP        | Mixed-integer non-linear programming. |
| PV           | Photovoltaic. |
| SDS          | Smart distribution system. |
| TMS          | Time Multiplier Setting |
| WT           | Wind turbine. |

### NOTATION

- **Index and set**
  - $\Omega / N_d$: Set/number of load buses.
  - $\Omega_s / N_s$: Set/number of substation buses.
  - $\Omega_B / B$: Set/number of time periods.
  - $\Omega_H$: Set of network branches indexed by $nm$.
  - $\Phi_{D_P}, \Phi_{D_R}, \Phi_{G}$: Uncertainty sets pertaining to the real and reactive power demand and DG generation.
  - $n, m$: Indices of nodes.
  - $b$: Index of time period running from 1 to $B$.
  - $N_g$: Number of DG units.
  - $N_l$: Number of linear segments for loss function approximation.
  - $l$: Index of intervals used for linear approximation of the loss function running from 1 to $N_l$.
  - $j$: Number of DOCRs.
  - $K, \Theta$: Constant values that are selected based on the operating characteristics of the DOCR.

- **Parameters**
  - $b_h$: Number of hours in period $b$.
  - $r_{nm}$: Resistance of the branch $nm$ in pu.
  - $\rho_{f_D}$: DG power factor at node.
  - $\rho_{f_{PV}}$: PV power factor at node.
  - $\rho_{f_{WT}}$: WT power factor at node.
  - $f_{nm}^{0}$: Initial status of a network switch associated with feeder $nm$: 1 closed; 0 open.
  - $N_{sw}$: Number of switching actions.
TABLE 4  How to coordinate protection relays in the optimal structure

| Line number | Relay operation time | TMS   | PS   | CTR   |
|------------|---------------------|-------|------|-------|
| 1          | 3                   | 0.696 | 1.693| 494.69|
| 2          | 2.4                 | 0.478 | 1.728| 605.16|
| 3          | 2                   | 0.471 | 1.774| 459.577|
| 4          | 1.8                 | 0.309 | 2.496| 503.696|
| 5          | 1.6                 | 0.607 | 1.491| 206.918|
| 6          | 1                   | 0.404 | 1.692| 154.607|
| 8          | 1.989               | 0.593 | 1.138| 464.608|
| 10         | 0.995               | 0.213 | 1.613| 575.984|
| 11         | 1.2                 | 0.321 | 1.03 | 623.814|
| 12         | 1.198               | 0.487 | 1.573| 160.602|
| 13         | 0.995               | 0.167 | 2.115| 594.246|
| 15         | 1.598               | 0.651 | 0.762| 327.788|
| 16         | 1.396               | 0.506 | 1.28 | 262.097|
| 17         | 1.197               | 0.535 | 1.534| 124.286|
| 18         | 2.906               | 0.507 | 1.653| 716.845|
| 19         | 2.673               | 0.619 | 1.665| 480.295|

TABLE 5  Partial results of switch status and security indexes of scenarios

| Model | Open switch | Network losses (kW) | Number of miss coordination |
|-------|-------------|---------------------|-----------------------------|
| Reconfiguration base [25–27] | 33, 34, 35, 36, 37 | 207.759 | Without coordination |
| Scenario 1 | 7, 9, 14, 28, 32 | 139.17 | 14 |
| Scenario 2 | 7, 10, 14, 36, 37 | 140.69 | 5 |
| Scenario 3 | 7, 10, 14, 36, 37 | 140.69 | 0 |
| Scenario 4 | 7, 9, 14, 28, 32 | 139.17 | 0 |

REFERENCES

1. Gangwar, P., Singh, S.N., Chakrabarti, S.: Multi-objective planning model for multi-phase distribution network under uncertainty considering reconfiguration. IET Sci., Meas. Technol. 13(12), 2070–2083 (2019)
2. Jose, J., Kowli, A.: Path-based distribution feeder reconfiguration for optimization of losses and reliability IEEE Trans. Power Delivery 14(1), 1417–1426 (2020)
3. Kavousi-Fard, A., Niknam, T., Khooban, M.H.: Intelligent stochastic framework to solve the reconfiguration problem from the reliability view IET Sci., Meas. Technol. 8(5), 245–259 (2014)
4. Ghaweta, A.: Optimal distribution feeder reconfiguration with optimal planning of distributed generation for loss reduction and voltage improvement using deferential evolution algorithm. Int. J. Forensic Software Eng. 1(1), 1 (2019)
5. Pegado, R., et al.: Radial distribution network reconfiguration for power losses reduction based on improved selective BPSO. Elsevier Power Syst. Res. 169, 206–213 (2019)
6. Ahmadi, H., Marti, J.R.: Minimum-loss network reconfiguration: A minimum spanning tree problem Sustainable Energy Grids Networks 1, 1–19 (2015)
APPENDIX

To achieve an overall optimal solution and low competition time running speed, this paper uses linear equations corresponding to non-linear equations to replace the non-linear equations of the reconfiguration step. Therefore, the problem presented in (2) is rewritten as a mixed-integer linear program. It should be noted that programming in the protected section was performed non-linearly using the water cycle algorithm. The function of the quadratic equation (2) can be modelled by a linear, piecewise function. The procedure is to divide the quadratic function into \( l \) linear pieces, to rewrite (2) as follows:

\[
\begin{align*}
\text{Max } & \psi_{nm,b}, q_{nm,b} = \frac{\psi_{nm,b}^+ - \psi_{nm,b}^-}{\psi_{nm,b}^+ - \psi_{nm,b}^-} \\
\text{s.t: } & \\
\sum_{i=1}^{N_l} \psi_{i,pl} r_{nm,b} \psi_{nm,b} = \frac{\sum_{i=1}^{N_l} \alpha_{nm,b}^+ \psi_{nm,b}^+ - \sum_{i=1}^{N_l} \alpha_{nm,b}^- \psi_{nm,b}^-}{\sum_{i=1}^{N_l} \alpha_{nm,b}^+ - \sum_{i=1}^{N_l} \alpha_{nm,b}^-} \\
\sum_{i=1}^{N_l} \beta_{nm,b}^+ \psi_{nm,b}^+ - \sum_{i=1}^{N_l} \beta_{nm,b}^- \psi_{nm,b}^- & \leq 1
\end{align*}
\]

\[
(A.1)
\]

\[
(A.2)
\]

\[
(A.3)
\]

\[
(A.4)
\]

\[
(A.5)
\]

\[
(A.6)
\]

\[
(A.7)
\]
APPENDIX B

Short-circuit current calculations (basic point-to-point calculation procedure):

Step 1. Determine the transformer full load amps (F.L.A.) from either the nameplate, the following formulas, or Table B.1:

\[ 3\phi \text{ Transformer } I_{F.L.A} = \frac{kVA \times 1000}{E_{F.L.A} \times 1.732} \]

\[ 1\phi \text{ Transformer } I_{F.L.A} = \frac{kVA \times 1000}{E_{F.L.A}}. \]

Step 2. Find the transformer multiplier. See Notes 1 and 2.

Note 1. Get %Z from the nameplate. Transformer impedance (Z) helps to determine what the short-circuit current will be at the transformer secondary. Transformer impedance is determined as follows: The transformer secondary is short-circuited. The voltage is increased in the primary until full load current flows in the secondary. This applied voltage divided by the rated primary voltage (times 100) is the impedance of the transformer.

Example: For a 480-V rated primary, if 9.6 V causes secondary full load current to flow through the shorted secondary, the transformer impedance is 9.6/480 = 0.02 = 2%Z.

Note 2. Also, UL 1561 listed transformers 25 kVA and larger have a ±10% impedance tolerance. Short-circuit amps can be affected by this tolerance. Therefore, for the high end of worst case, multiply %Z by 0.9. For the low end of worst case, multiply %Z by 1.1. Transformers constructed to ANSI standards have a ±7.5% impedance tolerance (two-winding construction).

Step 3. Determine by formula the transformer let-through short-circuit current. See Notes 3 and 4.

\[ I_{S.C} = \text{Transformer}_{F.L.A} \times \text{Multiplier}. \]

Note 3. Utility voltages may vary ±10% in power and ±5.8% for 120-V lighting services. Therefore, for the highest short-circuit conditions, multiply %Z by 0.9. For the low end of worst case, multiply %Z by 1.1. Transformers constructed to ANSI standards have a ±7.5% impedance tolerance (two-winding construction).

Note 4. Motor short-circuit contribution, if significant, may be added at all fault locations throughout the system. A practical estimate of motor short-circuit contribution is to multiply the total motor current in amps by 4. Values of 4–6 are commonly accepted.

Step 4. Calculate the “f” factor:

\[ f = \frac{1.732I_{F.L.A}}{C \times I_{L-N}} \]

Note 5. The L–N fault current is higher than the L–L fault current at the secondary terminals of a single-phase centre-tapped transformer. The short-circuit current available (I) for this case in Step 4 should be adjusted at the transformer terminals as follows: At L–N centre-tapped transformer terminals, \[ I_{L-N} = 1.5 \times I_{L-L} \] at transformer terminals. At some distance from the terminals, depending upon wire size, the L–N fault current is lower than the L–L fault current. The 1.5 multiplier is an approximation and will theoretically vary from 1.33 to 1.67. These figures are based on the change in turns ratio between primary and secondary, infinite source available, 0 ft from the terminals of the transformer, and 1.2 × %X for L–N versus L–L resistance and reactance values. Begin L–N calculations at transformer secondary terminals; then, proceed point to point.

Step 5. Calculate “M” (multiplier):

\[ M = \frac{1}{1+f}. \]

Step 6. Calculate the available short-circuit symmetrical RMS current at the point of fault. Add motor contribution, if applicable:

\[ I_{S.C, \text{sym}, \text{RMS}} = I_{S.C} \times M. \]

Step 6A. Motor short-circuit contribution, if significant, may be added at all fault locations throughout the system. A practical estimate of motor short-circuit contribution is to multiply the total motor current in amps by 4. Values of 4–6 are commonly accepted.

Single-phase short circuits:

Short-circuit calculations on a single-phase centre-tapped transformer system require a slightly different procedure than 3Φ faults on 3Φ systems.

- The proper impedance must be used to represent the primary system. For single-phase faults, a primary conductor impedance is considered from the source to the transformer and back to the source. This is compensated in the calculations by multiplying the 3Φ primary source impedance by two.
- The actual transformer resistance and reactance of the half-winding condition are different from the actual transformer resistance and reactance of the full winding condition. Thus, adjustment to the %X and %R must be made when considering line-to-neutral faults. The adjustment multipliers generally used for this condition are as follows:
  - bullet§1.5 times full winding %R on a full winding basis.
  - bullet§1.2 times full winding %X on a full winding basis.

TABLE B.1 Calculation method for short-circuit current attenuation index

| Short-circuit current attenuation index | Fault type       |
|----------------------------------------|------------------|
| \[ f = \frac{1.732I_{F.L.A}}{C \times I_{L-N}} \] | Three-phase      |
| \[ f = \frac{1.732I_{F.L.A}}{C \times I_{L-N}} \] | Phase-to-phase   |
| \[ f = \frac{1.732I_{F.L.A}}{C \times I_{L-N}} \] | Phase-to-ground  |

Note:

- C: constant from AWG kcmil for three single conductors three-conductor cable or conduit of “C” values; N: number of conductors per phase (adjust C value for parallel runs); L available short-circuit current in amperes at the beginning of the circuit; and E: voltage of circuit.

Page 1691
The impedance of the cable and two-pole switches on the system must be considered “both-ways” since the current flows to the fault and then returns to the source. For instance, if a line-to-line fault occurs 50 ft from a transformer, then the impedance of a 100-ft cable must be included in the calculation.