International Journal of Industrial Electronics, Control and Optimization © 2021 IECO
Vol. 4, No. 3, pp. 321-331, July (2021)

Reconfiguring Distribution Networks by Minimizing Power Loss and Considering Overcurrent Protection

Elham Khoshbakht Sangkar[1], Farhad Namdari[2, †], Meysam Doostizadeh [3]

[1, 2, 3] Department of Electrical Power Engineering, Engineering Faculty, Lorestan University, Khorram Abad, Iran.

ABSTRACT

This paper studies the reciprocal of distribution network protection and reconfiguration of an active distribution network (AND). Accordingly, a distribution network reconfiguration is carried out to find the optimal switching operations. Since the switching operations will change the network topology and the short circuit level of the buses, the protection coordination may be invalid. To address this issue, constraints of the coordination of the protection relays and fuses are formulated and added to the reconfiguration problem. Moreover, the nonlinear equations of the problem are linearized and transform the reconfiguration problem into Mixed-Integer Linear Programming (MILP) to achieve the global optimal solution. The proposed method was implemented on a 33-bus distribution network. The results clearly show the effectiveness of active and reactive power management in an intelligent distribution network considering protection concepts.

Article Info

Keywords:
Active distribution network, Mixed-integer linear programming, Protection coordination, Reconfiguration.

Article History:
Received 2020-10-29
Accepted 2021-04-05

I. INTRODUCTION

The smartness of distribution grids has significantly grown in recent years. This smart view will improve the operation of the grids in cases like reducing the level of blackouts at the distribution level, developing the use of renewable energy, random loads, and presenting solutions for the control and management of electrical energy consumption. Incorporating smartness into distribution grids makes them flexible to use renewable energy resources in low or medium voltage levels. One of the most effective techniques in smart power systems is a reconfiguration strategy [1]. With this respect, the open/close operation of breakers will be done by using operational improvements. It is clear, in this case, that configuration and reconfiguration will be changed. In distribution networks, reconfiguration changes the grid topology to improve the network operation, which will maintain the radial structure of the grid [2]. The resulting topology depends on different input parameters, where reconfiguration is based on changes in the operating conditions of the system in an hour, day, or season. Reconfiguration of distribution grids to reduce losses is reorganizing it; somewhere by reduction of losses, the grid radial structure is maintained, done by proper changes in the status of the breakers [3].

Reconfiguration is a combined nonlinear optimization problem with integer numbers [4], which is solved considering grid operation constraints to reach various purposes such as reducing losses [5], load balances [6], etc.

The reconfiguration of distribution grids to reduce losses was firstly introduced by Marilyn and Beck [7] in 1975, where after closing all the breakers, the breakers with the least current were opened one after the other, which was obtained from a DC load flow to reduce losses under various load conditions. Gosuami and Basu [8] presented a heuristic algorithm for reconfiguration by using a load flow program. Talesky and Rajisik [9] presented an optimization technique to determine the structure of a distribution system with minimum energy losses for a given period. Applied aspects of the optimal reconfiguration of the distribution systems were introduced by Brazen and Rajkovich [10]. Indeed, the reconfiguration is similar to the problem of optimal load flow. Various methods have been used to solve the reconfiguration problem, which can be divided into four general categories:

1. Heuristic methods [11]
2. Mathematical optimization methods [12]

† **Corresponding Author** : namdari.f@lu.ac.ir
Tel/Fax: +98-6633120005, Department of Electrical Power Engineering, Engineering Faculty, Lorestan University, Khorram Abad, Iran.

3. Metaheuristic or smart optimization methods [1], [13]
4. Combined methods [14], [15]

Load flow and short circuit calculations show that by changing grid configuration, the load currents and short circuit levels are changed, which may cause problems with the coordination of protection elements [6]. Thus, it is possible that by reconfiguring the grid topology, the designed protection system loses its efficiency, and the distribution grid is exploited in an unprotected state or the normal performance of the grid is disrupted [16].

To maintain the coordination between the protective elements and their correct functioning, the system can be classified into two categories [12]:

• A fully automatic distribution system that allows online changes in the relay settings after reconfiguration. In this case, using the design of the new protection system in the modified configuration, protection system settings are adopted in the new configuration [13].

• The distribution system has a semi-automatic control so that only the operator can change the relay settings.

The smart grid brings the ability to use different technologies for energy production and storage easily. Research studies on the reconfiguration of distribution systems have pursued various purposes, but most of them have not considered grid protection. In these studies, the researchers have mostly focused on whether the studied distribution system is equipped with a fully automatic system, so they have considered that the protection system will adapt itself to the new configuration [6]. An algorithm has been presented in [6] and [17] for designing a protection system for several different configurations. In this algorithm, besides coordinating the relays in the feed bus and determining the nominal value of the re-closers and fuses, the proper location of their installation is specified as well. After designing the protection system with these features, the authorized switching area of the automation system is defined and the protection system will function properly and desirably. The same approach was considered in [18]. The technique is referred to as the virtual microgrid system. Several factors are considered in the study, including the maximum load demand, the available power supply, and the operation cost. The restoration problem is posed as a MILP problem [19].

In [20], the genetic algorithm is used with a slight change in composition and mutation operators using a competition mechanism to solve the reconfiguration problem. The MILP problem is the problem of optimizing the value of a linear objective function of some integer/real-valued variables, which satisfy some linear (in) equality constraints. MILP solvers can contribute to finding the best differential characteristic of a cipher if the problem of finding the optimal differential characteristic of a cipher can be translated into a (not too large) MILP problem. To that end, the objective function should be set to an adequate strictly monotonic function of the characteristic probability, and the linear constraints should be configured to express the propagation of the differing values in the cipher. Therefore, to the modeled cryptosystem, the optimum differential characteristic probability would be returned by solving the model with an adequate MILP solver [21]. The linearization method is introduced to model the day-ahead scheduling of ADN as a MILP problem, in which the electricity purchasing cost, line switch operation cost, and responsive load subsidy cost of the power systems with wind power integrated are simultaneously optimized. The results under different uncertainties of loads and DGs, which are handled by the combined scenario and Monte-Carlo method, further verify the feasibility of the MILP model [22].

The necessity of this paper is modeled in randomized optimization problems, non-deterministic and random variables with a suitable distribution function so that the behavioral pattern of these variables can be expressed with different probabilities. It is necessary to increase the installation of these types of resources on grids to use the environmental benefits and low cost of distributed renewable energy resources. The thermal rating of the lines, voltage increase, and protection difficulties could be mentioned as some of the most important barriers to installing distributed generations (DGs) in grids. DG placement and installation methods are generally used to get the best location and the maximum active power to be installed in a particular configuration in the worst scenario. The solution to this problem has recently been discussed in [22].

In Table I, a comparison is made between this work and the previous research, and the comprehensiveness of the design of the reconfiguration distribution system protection (RDSP) proposed in this paper is demonstrated. Accordingly, the effect of reconfiguration on the network protection plan has not been studied in previous research. Neglecting the receptacle impact of network reconfiguration and protection may lead to missing the operation of protective devices. Therefore, to cover this research gap, the effects of distribution network reconfiguration on its protective coordination are considered in the proposed model. Also, the uncertainties and variations in the output power of the DG, photovoltaic (PV), and wind turbine (WT) are considered in this study. Moreover, an MILP formulation is presented to solve the proposed model. According to the contents of this paper, a two-step algorithm is proposed to establish coordination between the protection system and the network configuration. The first step is to determine the optimal reconfiguration to reduce system-wide losses. This is achieved by shortening the flow through the optimal feeders and exploiting the existing distributed renewable generation. In the second stage, the obtained makeup is examined from a protective point of view. At this stage, by determining the possibility of resetting all or several protection relays, the protective function of the network is feasible. Otherwise, if it is infeasible, the fault signal is sent to the first stage and another optimal reconfiguration is determined, which certainly has a higher loss rate. The details of the iteration

loop are fully explained in the simulation section.

In this paper, a new RDSP scheme is presented based on mathematical formulations. The contributions of the paper are highlighted below.

- Determining optimal reconfiguration of the distribution network considering fault occurrences so that the maximum possible value is retrieved and the new network reconfiguration has a minimum of active power losses.
- Coordinating the problem of overcurrent relays, and proper network switching.
- Linearization of the models, and comparison of the proposed model MILP with the nonlinear heuristic methods.
- Coordination modeling of protective elements taking into account the uncertainty of uncertainties of DG, PV, and WT in the reconfiguration distribution system.

TABLE I

COMPARISON OF THE PROPOSED MODEL WITH RECENT RESEARCHES.

Reference	Uncertainty Resource			Reconfiguration	Protection	Solving Strategy				Optimized Linearization of the model
	Wind	PV	DG			CSA	GA	ICA	MILP	
[14]			✓	✓		✓				
[15]			✓		✓			✓		
[23]			✓	✓	✓					
[24]			✓	✓			✓			
[27]			✓		✓					
[19]			✓						✓	✓
[22]			✓	✓					✓	✓
This Paper	✓	✓	✓	✓	✓				✓	✓

The structure of the papers is as follows. Section II discusses the reconfiguration and protection characteristics of the distribution grid. The constraints related to the operation and relay coordination are then formulated. The 33-bus test grid has been used to develop reconfiguration, design, and adjustment of the protection system according to the proposed concepts. Finally, the effects of protective constraints and considering the presented uncertainty for studying networks will be presented.

II. RECONFIGURATION OF DISTRIBUTION GRIDS

Reconfiguration in distribution grids to find the best switching using smart techniques is one of the vital issues in power distribution companies. Due to the appropriate protection coordination, limiting the grid's short circuit, and the problems of interconnected grids, operation of distribution grids is done in radial form. Moreover, there are several disconnecting switches in the grid with significant roles in managing the grid structure to reach the optimal form [2], [3], [23].

III. PROTECTION OF DISTRIBUTION SYSTEM

Protection is one of the most important needs for the acceptable operation of distribution grids. Security concepts of power system protection depend on parameters like sensitivity, selectivity, speed, and reliability. The protection system detects specific faults and limits any damage to power equipment. Each protection device installed in the distribution grid shall only detect faults on its downstream due to the radial property of the grid. A widespread protection philosophy is used to protect distribution grids, without any specific standard for overall protection [6], [13], [17], [18], [22].

IV. FORMULATION OF THE PROBLEM

The purpose of the optimization is the reconfiguration of the grid by reducing losses and enhancing the voltage profile while the security system works properly. In this paper, the objective function is optimized using the meta-heuristic optimization method.

$$F = \frac{\mathrm{F_{loss}}}{\mathrm{F_m}} + \sum_{j \in V, I, F} penalty - R \tag{1}$$

Where F_{loss} is the loss objective function, F_m is the total network loss in the initial settings, and *Penalty-R* is a permitted function of the problem constraint, including the usual constraints of the reconfiguration problem and the security constraints.

A. Loss of Objective Function

The main objective of the proposed model is to find the optimal configuration of the distribution network through the minimization of total system losses. Total system losses include total losses of all system branches that can be formulated as follows:

$$MinJ = \sum_t \sum_{nm \in \Omega_H} \sum_{s=1}^{N_S} \psi_s \; h_t \, r_{nm} (p^2_{nm,t,s} + q^2_{nm,t,s}) \tag{2}$$

Equation (2) is subjected to the following constraints. The Ψ_s index in the relationship indicates the probability of each scenario.

B. Power Flow Constraint

Constraints (3) and (4) present the active and reactive nodal power balance, respectively. Equations (5) and (6) describe the net nodal demand and line flow formulations, respectively. Constraints (7) and (8) present maximum active and reactive transmitted powers of connected lines, respectively. Equations (9) and (10) define the active and reactive power transferred through the substation, respectively.

$$\sum_{nm\in\Omega_H}\sum_{s=1}^{N_S}\Psi_s p_{nm,t,s}-\sum_{mn\in\Omega_H}\sum_{s=1}^{N_S}\Psi_s p_{mn,t,s}=L_{pn,t,s} \quad (3)$$

$$\sum_{nm\in\Omega_H}\sum_{s=1}^{N_S}\Psi_s q_{nm,t,s}-\sum_{mn\in\Omega_H}\sum_{s=1}^{N_S}\Psi_s q_{mn,t,s}=L_{qn,t,s} \quad (4)$$

$$L_{pn,t,s}=d_{pn,t,s}-P_{gn,t,s}, L_{qn,t,s}=d_{qn,t,s}-F(pf_{gn})P_{gn,t,s} \quad (5)$$

$$P_{nm,t,s}=F(v,i), Q_{nm,t,s}=G(v,i) \quad (6)$$

$$-y_{nm}p_{nm}^{\max}\le p_{nm,t}\le y_{nm}p_{nm}^{\max} \quad (7)$$

$$-y_{nm}q_{nm}^{\max}\le q_{nm,t}\le y_{nm}q_{nm}^{\max} \quad (8)$$

$$P_{sn,t,s}=\sum_{nm\in\Omega_H}\sum_{s=1}^{N_S}\Psi_s p_{nm,t,s} \quad (9)$$

$$Q_{sn,t,s}=\sum_{nm\in\Omega_H}\sum_{s=1}^{N_S}\Psi_s q_{nm,t,s} \quad (10)$$

1) Voltage limits: For each configuration operation of the grid, the value of the voltages in all the buses should remain in their pre-specified values:

$$V_{\min}\le|V_i|\le V_{\max} \quad (11)$$

Where V_{min} and V_{max} are the minimum and maximum bus voltages, respectively. To function, the permitted voltage ranges of the grid bus interface (18) are used as follows:

$$penalty-V=W\times(\sum_{i=1}^{Nbus}\max(V_i-V_{\max},0)+\sum_{i=1}^{Nbus}\max(V_i-V_{\min},0)) \quad (12)$$

Where W is the penalty coefficient assigned to the constraint in the distribution grid.

2) Lines capacity constraint: Given the thermal limit of line currents, overloading of any of the grid lines is not allowed:

$$|I_i|\le I_{\max,i} \quad (13)$$

where $I_{max,i}$ is related to the current of the lines. The penalty functions presented in Equation (20) are used for the proper functioning of the constraint of the current passing through the lines:

$$penalty-I=W\times(\sum_{i=1}^{Nb}\max(|I_i|-I_{\max,i},0) \quad (14)$$

3) Topology constraints: Reconfiguration of the distribution grid is a change in the grid topology, done by maintaining the radial structure of the grid to improve the system operation. This means that there is no loop in a distribution grid, and all buses must be connected to one of the main feeder buses. Regarding this, to remain in the radial direction of the grid, any restoration of the configuration should have the following equations:

$$z_{nm,b}=0 \quad (15)$$

$$z_{nm,b}+z_{mn,b}=y_{nm} \qquad \forall b,\forall nm\in\Omega_H \quad (16)$$

$$\sum_{b,nm\in\Omega_H}z_{nm,b}=1 \quad (17)$$

$$\sum_{nm,b\in\Omega_H}(y_{nm}-y_{nm}^0)^2\le N_{sw} \quad (18)$$

$$z_{nm,b},y_{nm}\in\{0,1\} \quad (19)$$

4) Constraints of protecting the distribution grid: At the beginning of each branch, there must be an overcurrent relay whose pickup current is greater than the maximum through-load current, considering the overload, and should be able to cut off the short-circuit current of the desired branch:

$$I_{pickup}=OLF\times I_{nom} \quad (20)$$

Where *OLF* is the overload factor, I_{nom} is the nominal current passing through the relay location, and *OLF* has different values for different protected types of equipment.

5) Protective constraints: The coordination of the protective equipment that should be considered in the formulation of constraints after reconfiguration. Warrington model relates to the time of the relay operation with the parameters TDS and I_b as follows:

$$t=c+\frac{k}{\left(\frac{I}{I_b}\right)^n-1}\times TDS \quad (21)$$

Where *TDS* represents the timing dial setting, *I* represents the current passing through the relay, I_b is the relay regulating current, *k* is the constant coefficient depending on the type of relay, *n* is a constant number depending on the type of relay reduction characteristic and *c* is a constant coefficient to consider the effect of friction and hysteresis. Various types of relays can be modeled using this equation.

6) Functional constraints and fuse coordination: The constraints related to fuse function and coordination are considered as follows:

$$Penalty-F=W_{1,1}\times\sum_{i=1}^{N_F}\max(1.25\times I_{i,IF},0)+W_{1,2}\times\sum_{i=1}^{N_{CF}}\max(MCT_{i,m}-0.75\times MMT_{i,b},0) \quad (22)$$

According to [26], to achieve the fuse-fuse coordination for the same short-circuit connection, the maximum cut time (MCT) of the fuse must not exceed 75% of the time required for melting the fusing element. One can examine the coordination of two or more fuses by plotting time-current characteristic of them in the logarithmic diagram.

The constraints related to the grid fuses are composed of two parts: the first part is intended to prevent the operation of the fuse under load, where a maximum of 25% of the overload is predicted for the grid in the new reconfiguration. The second part intended for reconfiguration of the primary/backup fuses is in coordination with the new conditions and the property of selectivity is observed.

The features of the conventional protection system in distribution grids show that the coordination constraints and the functionality of the equipment are formulated in the normal way and added to the reconfiguration problem. In this study, as the studied grid is balanced, three-phase, short-circuit and the three-phase fault are symmetric, it should be noted that the load current is ignored in the state of the fault.

A. Linearized Model

In the proposed model, equations have a nonlinear structure. This causes the nonlinear problem, so using conventional nonlinear programming (NLP) solver engines with the general algebraic modeling system (GAMS) software produces two major faults that are [24]:

Due to the nonlinear constraints of the area, the probability is non-convex, so it is possible to stop the solution after finding the local optimum with the NLP solution engine.

- Given the numerical solution methods for repetition for nonlinear problems, the problem-solving process is long considering time; therefore, the problem implementation speed is low.
- In this paper, the use of linear equations corresponding to nonlinear equations is proposed as an alternative to nonlinear equations to have an optimal global response and high implementation speed. Thus, the problem presented in Section I is rewritten as a linear problem with integer numbers. The second-order function of Equation (2) can be compared with the piecewise-linear function of the first-order loss function. In doing so, assume that we put linear sections l for the powerful currents $p_{nm,t,s}$,$q_{nmt,s}$, and lets them as follows:

$$J=\sum_t\sum_{nm\in\Omega_H}\sum_{s=1}^{N_s}\Psi_s h_t r_{nm}\left(\sum_{l=1}^{N_l}\alpha^l_{nm,t,s}p^l_{nm,t,s}+\beta^l_{nm,t,s}q^l_{nm,t,s}\right) \quad (23)$$

If:

$$p_{nm,t,s}=\sum_{l=1}^{N_l}p^l_{nm,t,s} \qquad \forall t, nm\in\Omega_H \quad (24)$$

$$q_{nm,t,s}=\sum_{l=1}^{N_l}q^l_{nm,t,s} \qquad \forall t, nm\in\Omega_H \quad (25)$$

$$0\le p^l_{nm,t,s}\le p^{l_{\max}}_{nm,s} \qquad \forall t, nm\in\Omega_H, l=1,\ldots,N_l \quad (26)$$

$$0\le q^l_{nm,t,s}\le q^{l_{\max}}_{nm,s} \qquad \forall t, nm\in\Omega_H, l=1,\ldots,N_l \quad (27)$$

Equation (23) shows the objective function of the problem, which corresponds to the objective function of the nonlinear problem. The losses are shown by the piecewise-linear method in Figure 1, and Equations (24) and (25) included linear-piecewise load-distribution equations. Thus, with the coefficients of the line slope $\propto^l{}_{nm,t,s}$ and$\beta^l{}_{nm,t,s}$, we express the piecewise-linear I. The remaining constraints of the proposed model are linear and the flowchart of the proposed model is presented in Figure 2.

According to the above description and the mathematical modeling 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 the objective function in GAMS software and a set of new structures are provided. The first solution has the least loss. The second, pay attention to the network's new structure, including the original and the reconfigured structures, programming is performed in MATLAB to minimize the loss with protection coordination optimal.

The flowchart of the proposed algorithm is illustrated in Figure 2 to indicate the implementation.

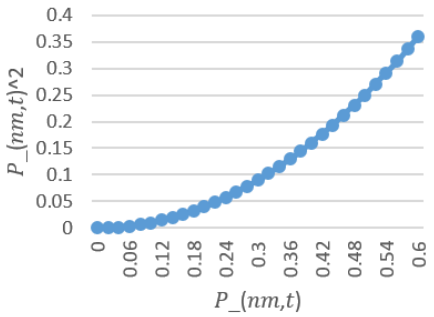


Fig. 1. Piecewise-linear approximations of the second-order equation.

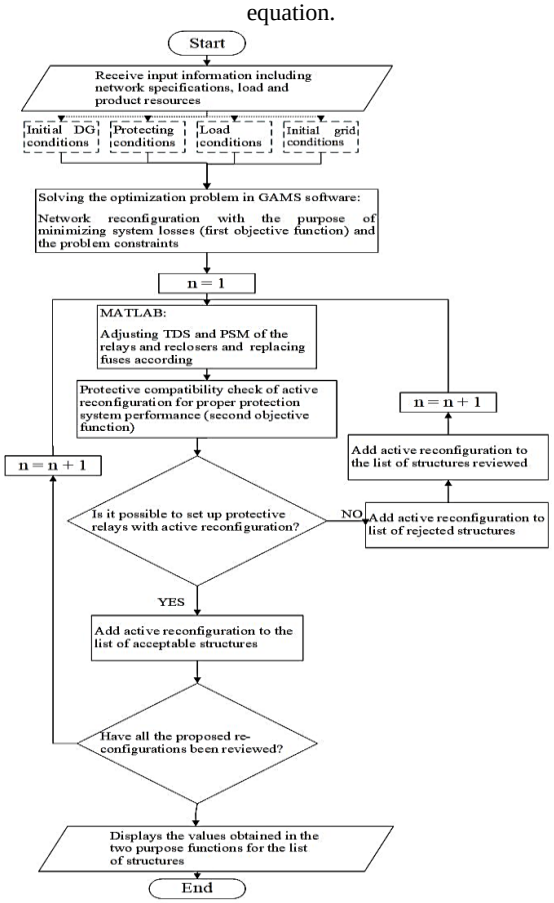


Fig. 2. The flowchart of the suggested method.

V. Simulation Results

In this paper, two MATLAB and GAMS software packages were used together for simulation, where GAMS was used to perform optimization and protection requirements of the load flow. The proposed problem is implemented in a 33-bus radial distribution grid displayed in Figure 3. The active and reactive loads of peak momentum are presented in [25]. The base power and voltage are 1 MW and 12.66 kV, respectively. The base curve for the predicted daily charge demand in Figure 4 and the prediction of wind turbine and photovoltaic power is evaluated. In this grid, there are 33 closed normal keys and 5 normal open keys that should be controlled during optimization. The proposed grid includes both active and reactive loads [26]. According to the grid's basic information, there are 3 or 4 distribution lines connected to some of the

buses that could be switched. Also, the total number of switchings is limited. Therefore, the best times and lines that should happen are selected. As the number of switchings is limited and only allows the power to be received at any point on one side, the lines are disconnected in the studied intervals. Moreover, by providing the load distribution equations for the linearization and definition of the switching of the grid similar to the other methods stated, the optimal overall point is obtained. In the proposed model, the parameters with uncertainty are quantified according to the probability distribution functions. The Weibull distribution function is used for the wind turbine, and the normal distribution function is used for the photovoltaic. All load, photovoltaic, and wind speed input information, as shown in Figure 4 for 24 hours a day, is also examined in a few stochastic samples in demand Figure (a-5), photovoltaic Figure (b-5), and wind turbine Figure (c-5). Finally, by reviewing the grid reconfiguration and considering the uncertainty scenarios of the active distribution grid, the best mode for interconnecting the branches in 1-hour and load the current diagram is shown in the figure6; for the rated current line is selected and is designated as I_n.

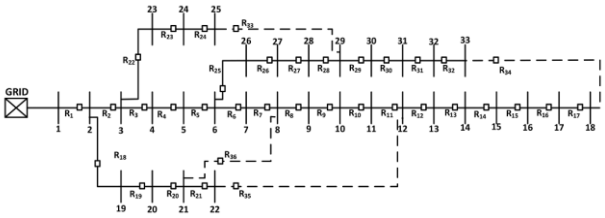


Fig. 3. The 33-bus distribution grid.

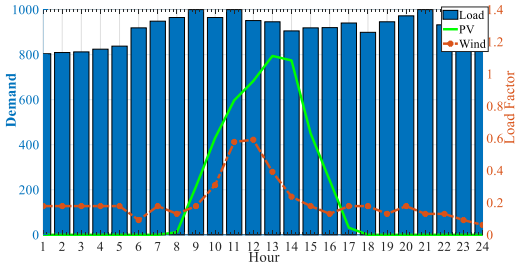
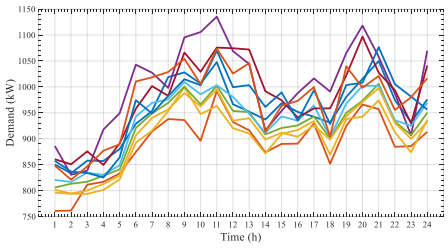
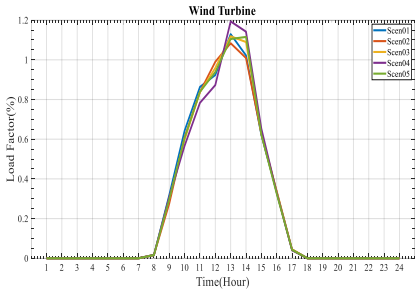


Fig. 4. Estimated grid demand and produced power [27].

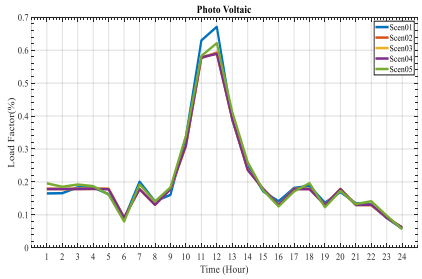
In the present paper, a relay is considered in the main supply bus as the primary protection of the entire grid, dispersed products in bus 22 and 30, two wind turbines in buses 10 and 14, and a solar cell in bus 19. The relays are used as main protection and backup in switching buses. A genetic algorithm (GA) is used as an optimization tool, and the objective functions are to satisfy formulated constraints. Generally, 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. Two approaches are defined by linear and nonlinear optimization methods based on artificial intelligence to show the performance of the proposed model. In the first case, the formulated reconfiguration is solved without any protective restrictions. In the second case, the reconfiguration problem is solved considering protective constraints.



(a) Demand



(b) Wind Turbine



(c) Photo Voltaic

Fig. 5. Predicting demand, wind turbine, and photovoltaic production capacity in 5 stochastic samples.

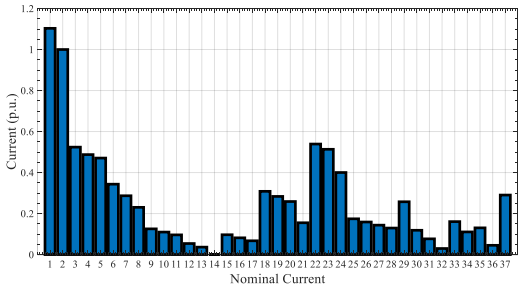


Fig. 6. The load current diagram at hour 1.

1) The first case

In this section, the reconfiguration problem of reducing losses and improving the voltage profile of the 33-bus grid is solved regardless of the protective constraints. Table II shows the keys obtained from the solution of the nonlinear optimization problem, according to the meta-heuristic algorithms, compared with the results obtained in the scientific references [28]. This algorithm has the necessary efficiency in solving the problem of reconfiguration in the grid. Figure 7 shows the process of minimizing the voltage profile by the algorithms, without the presence of protection utilizing backward-forward sweep load flow for this case. Comparing the voltage profiles in the three samples of the studied algorithm shows that in the first iterations, the value of the objective function is not less than one; in subsequent

iterations, the value of the objective function decreases dramatically. The minimization process continues until it is repeated until the objective function reaches its optimal value.

In repetitive numerical solution methods for nonlinear problems, the problem-solving process is time-consuming [24], so the speed of execution of the problem decreases. In this research, to have the optimal global solution and high execution speed, it is suggested to use linear equations instead of nonlinear equations. Hence, the proposed problem is rewritten as a linear problem mixed with integers.

TABLE II

RESULTS OF NONLINEAR AND LINEAR OPTIMAL RECONFIGURATION FOR REDUCING LOSSES, REGARDLESS OF PROTECTIVE CONSTRAINTS.

Problem Solving Method	Maneuvered Switched	Real Power loss(kW)	$V_{min}(p.u.)$
Genetic Algorithm Imperialist Competitive Algorithm	6-13-17-35-37	158.3641	0.9312
Crow Search Algorithm	7-9-13-28-32	143.5327	0.9404
The proposed Model	7-9-14-28-32	139.9814	0.9413
	14-28-33-35-36	139.5384	0.9240

As can be seen, each of these objective functions has been able to have positive effects on improving the state of the network from a unique perspective. However, the problem here is that each of these objective functions, after single-objective optimization, reaches a different and optimal keying pattern. In other words, if it certainly does not happen for all objective functions, the optimal switching patterns found in this objective function will likely be different. However, it is ultimately required to provide an optimal switching pattern for the entire network so that all the objective functions of the problem are performed to a large extent. One way to respond to this need is to provide a multi-objective optimization framework.

2) Second case

In this case, the optimal reconfiguration problem for a 33-bus grid has been solved for optimizing the total losses of this grid and considers the protection constraints.

The proposed model considers grid configuration protective problems online with the presence of any distributed products for using a reactive-active distribution network. By solving optimization problems in the studied system, there is a series of switching operations. This switching is done due to a change in the graph and a change in the power of the short-circuit connections. Changes in the short circuit power due to load discharges cause key switching. It is impossible to change the settings of all the relays in a microgrid or distribution network. Our study period is a short-term system operation and a limited number of keys have this feature. Measurements are made to protect at the maneuvering points, and then the protection relays are placed at the same points to indicate the configuration. Other protection architecture is based on using fuses.

After calculating the nominal current, we dealt with the grid fault, which is the first step in applying the fault on the grid. To apply faults on the grid in a bus, for example, in bus 4, faults are generated, and according to the loop and node rules, the currents passing through the branches are obtained.

Now, with the current lines in the event of a fault in the grid and having the nominal current obtained in the previous step, one can express protection based on the Warrington equation (16). This equation expresses the fuses coordination in the event of a fault so that when a fault occurs on a line or a student bus, the closest fuses act to the fault location at a specific time if these fuses have a functional disruption. In the next few moments, the fuses of the higher lines are involved.

Finally, the result of the nominal flow fault can be seen in Table III and Figure 8. As expected, the value of the objective function is increased by considering the new constraints. Then, considering the protection constraints causes a reduction in grid losses that leads to more constraints on the optimization problem. However, in this configuration, the network losses are reduced by about 30 kW compared to the initial case of the network. The use of protective and coordination devices should be examined to confirm the proper functioning of the protective system in this case.

As there is the necessary time interval (margin = 0.3 s) between their performance, one can conclude that the coordination of its protected elements is low.

TABLE III

COMPARING RECONFIGURATION RESULTS TO REDUCE THE LOSSES WITH OTHER REFERENCES, CONSIDERING THE PROTECTIVE CONSTRAINT.

Problem Solving Method	Maneuvered Switched	Real Power loss(kW)	$V_{min}(p.u.)$
Crow Search Algorithm	6-13-21-32-37	165.0138	0.9218
Genetic Algorithm Imperialist Competitive Algorithm	7-13-17-21-28	158.8401	0.9327
Fault in the fourth bus OF the proposed model	6-11-34-36-37	145.4154	0.9373
	3-14-28-33-36	139.98	0.9413

Table IV shows the backup relays of each relay and Table V shows the settings of each relay.

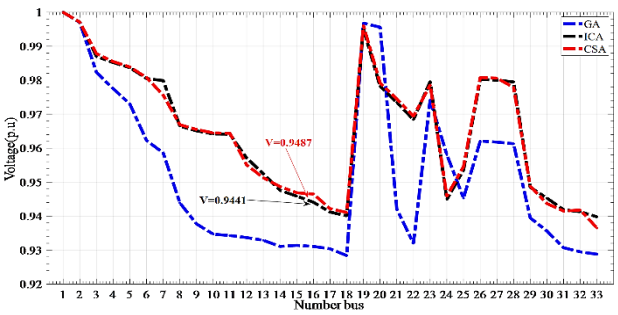


Fig. 7. Comparing the voltage profile with multi-objective reconfiguration regardless of protective constraints.

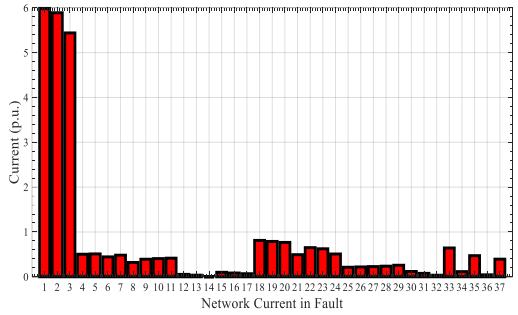


Fig. 8. Nominal current fault in the bus4, 1-hour interval.

Setting the Priority and Short Circuit Level: To determine the path of current flow to energize the network busses, the radial diagram of the existing structure is first plotted and the corresponding graph is drafted. Table IV shows optimal structures.

Considering the radial structure of the DN, the obtained graph is a 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 3, the short circuit level at the installation site of the protection relays is shown in Table IV, which introduces the line numbers, the beginning and end buses, the short circuit current level, and the line number in which the backup relay of each line is contracted. As it turns out, except for the line 1 relay, the backup relay number of each line is determined by the current path.

TABLE IV
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

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

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 VI. The system loss is equal to 139.98 kW in this case. The table presents the optimization results for the second case. By comparing the two tables, it is revealed that the operating time of the main relay, in this case, is equal to 3, implying a decrease of 28.57% versus the first case. The reason for this is a reduction in the strength of the network tree branches so that all branches have almost the same resistance. In this case, the total operating time of the system is 53. Overall, at each stage after the coordination of the protection devices, the graph corresponding to the new grid configuration is checked. If the previous configuration loading is declared infeasible in the grid, it will be done with feedback to the reconfiguration of the linear optimization that is the link between MATLAB and GAMS. According to the objective function and the problem constraints, a new topology is suggested at each step of the reconfiguration according to the observations.

TABLE V
COORDINATE PROTECTION RELAYS IN THE BASE STRUCTURE.

Line Number	Relay Operation Time	TDS	PS	CTR	Line Number	Relay Operation Time	TDS	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

TABLE VI
COORDINATE PROTECTION RELAYS IN THE OPTIMAL STRUCTURE.

Line Number	Relay Operation Time	TDS	PS	CTR	Line Number	Relay Operation Time	TDS	PS	CTR
1	3	0.696	1.693	494.69	20	2.459	0.669	0.991	611.2
2	2.4	0.478	1.728	605.16	21	1.591	0.557	0.753	503.225
3	2	0.471	1.774	459.577	22	2.206	0.469	1.554	611.088
4	1.8	0.309	2.496	503.696	23	2.001	0.624	0.997	485.658
5	1.6	0.607	1.491	206.918	24	1.8	0.496	1.948	316.715
6	1	0.404	1.692	154.607	25	1.395	0.44	0.805	590.828
8	1.989	0.593	1.138	464.608	26	1.198	0.328	1.157	541.405
10	0.995	0.213	1.613	575.984	27	0.997	0.255	1.613	438.261
11	1.2	0.321	1.03	623.814	29	1.394	0.364	1.734	391.982
12	1.198	0.487	1.573	160.602	30	1.194	0.401	0.948	434.428
13	0.995	0.167	2.115	594.246	31	0.997	0.341	1.385	284.506
15	1.598	0.651	0.762	327.788	33	2.202	0.559	2.192	322.19
16	1.396	0.506	1.28	262.097	34	1.789	0.494	1.279	473.377
17	1.197	0.535	1.534	124.286	35	1.403	0.589	0.949	244.231
18	2.906	0.507	1.653	716.845	36	0.989	0.287	1.106	496.125
19	2.673	0.619	1.665	480.295	37	1.614	0.472	1.143	472.016

The results of the surveys conducted in the sample distribution network are as follows:

- The main problem that occurs in reconfiguring without considering the protective restrictions and in most cases is related to the operation of the fuses. In solving the reconfiguration without considering the protection constraints, we can pay attention to several scenarios in which, in all cases, several network fuses operate under load and cut off the load. Discrepancies are not shown.
- Although studies have shown that the displacement of short circuit levels depends on different reconfigurations and also depends on the protection system in the network, there is a possibility of disruption in the coordination of this equipment, but by examining the simulation results of the proposed model in different scenarios of relay, inconsistency or recloser was not observed with fuses.
- Therefore, by using the proposed method, it is possible to ensure the correct operation of the protection system by performing reconfiguration in addition to using the advantages of this method in the operation of distribution networks.
- The proposed method is a method that will allow changing the makeup without prior planning. Also, if the network layout is changed with prior planning, the network can be used more efficiently and economically than the proposed method.
- Other features of the MILP method with the above problems include (1) very low solution execution time, (2) having an absolute optimum solution, (3) ability to run on a large network, and (4) providing a solid model with simple equations and methods.
- In the studied systems, the operating time is improved compared to another reference [11-15], which indicates the efficiency of the linear programming method developed in the

- GAMS environment because of applying a more accurate approach to solving coordination of overcurrent relays problem by exact mathematical methods developed in the GAMS environment.

VI. CONCLUSIONS

This paper analyzed the coordination of network structure with two approaches to minimizing losses and reducing the operating time of protection relays. A new method is proposed according to the branch switch optimization algorithms and sequential branch opening to solve reconfiguration. Using advanced technologies for data collection, the implementation of decision-making algorithms, and dynamic load distribution control, power outages in smart grids are minimized. By comparing the simulation results, one can understand that the mentioned linearization method has a good efficiency in solving the reconfiguration problem. Protective constraints include equipment performance and coordination of protective tools and formulation added to the reconfiguration problem. By examining the simulation results in the study of the sample grid and different scenarios, there was no lack of coordination among the elements. Studies show that despite short-circuit surface displacement that depends on different configurations and grid protection, there is a potential disruption in the coordination of the equipment. By presenting the optimal settings of the sample testing system, this paper accurately performs minimum active power loss and optimal voltage characteristics with protective devices and renewable energies.

According to research carried out in this paper, it is suggested to study the effect of unbalanced loads and the associated uncertainties and to include reliability evaluation in the proposed model in future research.

References

[1] A. Kavousi-Fard, et al, "Multi-objective probabilistic reconfiguration considering uncertainty and multi-level load model," *IET Science, Measurement & Technology*, vol. 9, no. 1, pp. 44-55, 2014.

[2] I. Ben Hamida, et al, "Optimal integration of distributed generations with network reconfiguration using a pareto algorithm," *International Journal of Renewable Energy Research*, Vol. 8, No. 1, pp. 345-356, 2018.

[3] M. Mohammadi, et al, "Distribution automation planning and operation considering optimized switch placement and feeder reconfiguration strategies from reliability enhancement perspective," *IOS Press*, vol. 35, pp. 3493-3506, 2018.

[4] F. Xinming, et al, "Application of discrete learning optimization algorithm to distribution netwrk reconfiguration considering distrebuted generation[J]," *Power System Protection and Control*, vol. 46, no. 8, pp. 156-163, 2018.

[5] S. P. Ghanegaonkar, V. N. Pande, "Optimal hourly scheduling of distributed generation and capacitors for minimisation of energy loss and reduction in capacitors switching operations," *IET Generation, Transmission & Distribution*, vol. 11, no. 9, pp. 2244-2250, 2017.

[6] S. Mohanty, et al, "A novel meta-heuristic approach for load balancing in cloud computing," *IGI Global*, vol. 8, no. 1, pp. 29-49, 2018.

[7] A. Merlin, "Search for a minimal-loss operating spanning tree configuration for an urban power distribution system. *Proc. of 5th PSCC*, vol. 1, pp. 1-18, 1975.

[8] S. K. Goswami, S. K. Basu, "A new algorithm for the reconfiguration of distribution feeders for loss minimization," *IEEE Transactions on Power Delivery*, vol. 7, no. 3, pp. 1484-1491, 1992.

[9] R. Taleski, D. Rajicic, "Distribution network reconfiguration for energy loss reduction," *IEEE Transactions on Power Systems*, vol. 12, no. 1, pp. 398-406, 1997.

[10] V. Borozan, N. Rajakovic, "Application assessments of distribution network minimum loss reconfiguration," *IEEE Transactions on Power Delivery*, vol. 12, no. 4, pp. 1786-1792, 1997.

[11] F. Ding, K. A. Loparo, "Hierarchical decentralized network reconfiguration for smart distribution systems—Part I: Problem formulation and algorithm development," *IEEE Transactions on Power Systems*, vol. 30, no. 2, pp. 734-743, 2014.

[12] P. Mariaraja, T. Manigandan and S. Thiruvenkadam, "An expert system for distribution system reconfiguration through fuzzy logic and flower pollination algorithm," *SAGE Publications*, vol. 51, pp. 371-382, 2018.

[13] S. S. F. Souza, R. Romero and J. F. Franco, "Artificial immune networks copt-ainet and opt-ainet applied to the reconfiguration problem of radial electrical distribution systems," *Electric Power Systems Research*, vol. 119, pp. 304-312, 2015.

[14] K. S. Kumar, T. Javabarathi, "Power system reconfiguration and loss minimization for a distribution systems using bacterial foraging optimization algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 36, pp. 13-17, 2012.

[15] X. Xiaoqin, et al, "Reconfiguration of two-voltage distribution network based on cuckoo srarch and simulated annealing algorithm," *Power System Protection and Control*, vol. 48, pp. 11, 2018.

[16] G. J. Peponis, M. P. Papadopulos and N. D. Hatziargyriou, "Optimal operation of distribution networks," *IEEE Transactions on Power Systems*, vol. 11, no. 1, pp. 59-67, 1996.

[17] F. Capitanescu, et al, "Assessing the potential of network reconfiguration to improve distributed generation hosting capacity in active distribution systems," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 346-356, 2014.

[18] S. M. Hadad Baygi, J. Farzane, "Application of artificial intelligence techniques for optimum design of hybrid grid-independent PV/WT/battery power system," *International Journal of Industrial Electronics, Control and Optimization*, Vol.3, no. 3, pp. 275-289, 2020.

[19] A. Bu Jubarah, M. Al-Muhaini and I. M. Elamin, "A MILP-based approach for virtual microgrid restoration," *IEEE Access*, vol. 8, pp. 116695-116703, 2020.

[20] S. K. Bhattacharya, S. K. Goswami, "Distribution network reconfiguration considering protection coordination constraint," *Electric Power Components and Systems*, vol. 36, no. 11, pp. 1150-1165, 2008.

[21] E. Bagherzadeh, Z. Ahmadian, "MILP-based automatic differential search for LEA and HIGHT block ciphers," *IET Information Security*, vol. 14, no. 5, pp. 595-603, 2020.

[22] X. Qiao, et al, "Optimal scheduling of distribution network incorporating topology reconfiguration, BES and load response: A MILP model," *CSEE Journal of Power and Energy Systems*, pp. 1-12, 2020.

[23] R. P. Broadwater, et. Al, "An expert system for integrated protection design with configurable distribution circuits. I, " *IEEE Transactions on Power Delivery*, vol. 9, no. 2, pp. 1115-1121, 1994.

[24] W.-M. Lin, F.-S. Cheng and M.-T. Tsay, "Distribution feeder reconfiguration with refined genetic algorithm," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 147, no. 6, pp. 349-354, 2000.

[25] D. Zhang, Z. Fu and L. Zhang, "An improved TS algorithm for loss-minimum reconfiguration in large-scale distribution systems," *Electric Power Systems Research*, vol. 77, no. 5-6, pp. 685-694, 2007.

[26] J. S. Savier, D. Das, "Impact of network reconfiguration on loss allocation of radial distribution systems," *IEEE Transactions on Power Delivery*, vol. 22, no. 4, pp. 2473-2480, 2007.

[27] J. J. Shea, "Protection of electricity distribution networks, 2nd ed," *IEEE Electrical Insulation Magazine*, vol. 21, no. 2, pp. 55–55, 2005.

[28] GAMS, 2011. [Online]. Available: http://www.gams.com.

Abbreviations:

$W_{1,1}$: Fine factor related to fuse performance under normal conditions.

N_F : A total number of grid fuses.

$I_{i,nf}$: The nominal current of the i-th fuse and $I_{i,If}$, the passing current from the same fuse.

$W_{1,2}$: The penalty factor is related to the lack of coordination between fuses in tandem.

N_{CF} : The number of pairs of tandem fuses.

$MCT_{i,m}$: Maximum time needed for a downstream fuse or main protection.

$MMT_{i,b}$: Minimum time required for melting the fuse element of the upstream or the backup fuse.

t_{margin} : The security margin of time.

Variables: Variables based on pre-unit (p.u).

$n, m, P_{nm,t,s}, Q_{nm,t,s}$: The active and reactive power passing through the line at the two ends of the bus.

$p^{l}_{nm,t,s}, q^{l}_{nm,t,s}$: Active and reactive power linear approximation.

$P_{sn,t,s}, Q_{sn,t,s}$: The active and reactive power of the reference bus.

$d_{pn,t}, d_{qn,t}$: Injection of active and reactive power.

y_{nm}, z_{nm} : The binary variable in the feeder connection status: 1 if connected and zero if disconnected.

Parameters: Parameters are based on pre-unit

h_b : Number of hours of time period.

r_{nm} : Resistance of each branch.

N_{sw} : Number of switching operations.

PD, QD: Active and reactive power consumed.

$V_{\min}, V_{\max}$: The minimum and maximum voltage range.

Collections and indices:

$\phi_n, \phi_t, \phi_l, \phi_k$: Bus set, time, line, and linearization.

n, m: Bas counter.

t : Time.

l, k: Line, Number of Linearization



Elham Khoshbakht received the BSc and MSc degrees in Electrical Power Engineering from Lorestan University in 2015 and 2018, respectively. She started her Ph.D. in Electrical Power Engineering in 2019 at Lorestan University. She has published 6 technical papers at international conferences. Her fields of interest are Active Distribution Networks, Smart Grids, Power System Protection, and Power System Reconfiguration.



Farhad Namdari received the BSc from Iran University of Science and Technology (IUST) in 1995 and the MSc from Tarbiat Modarres University (TMU), Iran in 1998, and the Ph.D. from IUST in 2006 all in Electrical Power Engineering. He is currently working as an Associate Professor with the Lorestan University. Dr. Namdari has published more than 100 technical papers in valuable journals and conferences. His fields of interest are Power System Protection, Power System Transients, Smart Grids, and Artificial Intelligent (AI) Applications in Power Systems, Power System Optimization, and Wide Area Monitoring, Protection, and Control of Power Systems.



Meysam Doostizadeh received the MSc and Ph.D. degrees in Electrical Engineering from the University of Tehran, Tehran, Iran, in 2012 and 2016, respectively. He is currently an Assistant Professor with the Engineering Faculty, Lorestan University, Iran. His research interests include electricity markets, smart grid technologies, and integration of renewable energy into power systems.

IECO
This page intentionally left blank.