

# An Operational Planning Approach Distribution Automation Considering the Contribution of Demand Response Programs in Service Restoration Process

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**Abstract:** This paper proposes an advanced distribution automation planning problem in which emergency-based demand response plans are incorporated during service restoration process. The fitness function of this planning problem consists of various costs associated with fault occurrence in electric distribution systems consisting of the total yearly cost of customers' interruptions, the total annualized investment cost of control and protection devices deployment, including sectionalizing switches, circuit breakers, and fuses and the total annual cost of performing emergency-based demand response programs in the service restoration process. Moreover, the customers' behavior in participating in the service restoration process is also modeled through using an S-function. The proposed advanced distribution automation planning method is implemented on the fourth bus of the Roy Bilinton test system in order to evaluate its efficacy. The obtained results show that the reliability indices and the total cost of distribution automation are reduced by about 9% and 12% more than the published methods for distribution automation, respectively.

**Keywords:** Power System Reliability, Distribution Automation, Sectionalizing Switch, Emergency-Based Demand Response Programs.

## Nomenclature

Notations used throughout this paper are introduced below for quick reference.

### Sets:

$\mathcal{Q}^{LP/Ln}$	Set of network load points/lines.
$\mathcal{Q}^{ID}$	Set of distribution automation devices installed at the network.
$\mathcal{Q}^{Yr}$	Set of planning years.
$\mathcal{Q}^{F/CB}$	Set of candidate locations of fuses/ circuit breakers.
$\mathcal{Q}^{Cnt}$	Set of contingencies in an electric distribution network.

### Constants:

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$P_{ij}/Q_{ij}$	Demand active/reactive power of load point $i$ in year $j$ .
$n_j^{Cust}$	Number of customers connected to the $j$ -th bus.
$C_{ij}^m$	Maintenance cost for equipment $j$ in year $i$ .
$\rho_{ij}$	Penalty charge rate should be paid to interrupted customers connected to $i$ -th bus in year $j$ .
$\rho_{ij}^{inc}$	Incentive rate that should be paid to customers connected to bus $j$ in the $i$ -th year.
$\lambda_{ki}$	Failure rate of the $k$ -th equipment in the $i$ -th year.
$C_i^{MS/AS}$	Investment cost of installing a manual/automatic switch at the $i$ -th candidate location.
$C_i^{CB/F}$	Investment cost of installing a circuit breaker/fuse at the $i$ -th candidate location.
$PW_i$	The present worth value coefficient for $i$ -th year of the DA planning period.
$V_j^{\max/\min}$	Minimum/maximum acceptable voltage level at bus $j$ .
$I_j^{\max/\min}$	Minimum/maximum acceptable current

	level of line $j$ .
$P_j^{RD,max}$	Maximum allowable demand can be reduced by the customers connected to load point $j$ .
$Y_{jl}/\theta_{jl}$	The admittance magnitude/angle between bus $j$ and $l$ .
$Bgt^{DA}$	Total available distribution automation budget.

**Functions:**

$OF$	Objective functions of the problem.
$C^{int}$	Total customers interruption cost.
$C^{DA}$	Total distribution automation cost.
$C^{EBDR}$	Total emergency-based demand response programs cost.
$C^{INV}/C^M$	Investment/maintenance cost of distribution automation.
$SAIDI$	System average interruption duration index.
$SAIFI$	System average interruption frequency index.
$AENS$	Average energy not supplied index.

**Variables:**

$ot_{ijk}$	Outage time experienced by customers connected to load point $i$ in case of fault occurrence on component $k$ during $j$ -th year of the planning period.
$pd_{ijk}$	Participation duration time of customers connected to bus $i$ in case of fault occurrence on component $k$ during $j$ -th year of the planning period.
$\omega_i^{MS/AS/F/CB}$	Binary variable that equals to one if a manual switch/ automatic switch / fuse/ circuit-breaker installed at the $i$ -th candidate location.
$P_{ijk}^{RD}$	The amount demand can be reduced by the customers connected to load point $j$ in case of failure occurrence in component $k$ during the $i$ -th year.
$V_{ijk}/\delta_{ijk}$	Voltage level/angle of bus $i$ in case of contingency $j$ for in the $k$ -th year.
$I_{ijk}$	Current level of line $i$ in case of contingency $j$ in the $k$ -th year.
$P_{ijks}^{sub} / Q_{ijks}^{sub}$	Active/reactive power injected from the upstream grid at bus $i$ during restoration process of contingency $j$ in year $k$ .

**1 Introduction**

TRADITIONAL electric distribution systems (EDSs) possess a time-consuming reaction to system failures. Thus, the outage duration time for customers, especially digital consumers, is undesirably high that is one of the main motivations for developing smart power distribution grid [1]. In a smart grid, real-time monitoring, measurement, and control of the grid events are accomplished automatically. Moreover, self-healing feature of the smart grid aims at accelerating the execution of the fault detection, isolation, and service

restoration function (FLISR). Thus, the reliability level of EDSs will be improved because of the reduction of customers' interruption time [2].

In order to attain such benefits, the current power grid should be modified and upgraded [3]. In fact, once a fault occurs, after fault detection and isolation, the service restoration process is performed through conducting a bunch of switching maneuvers in order to re-energize the interrupted customers as much as possible. This function is a relatively sluggish process in the legacy power grid. In recent years, advanced distribution automation (ADA) is proposed as the first step toward realizing such EDSs. Indeed, ADA leads to declining the expected interruption time through incorporating advanced monitoring, protection, and control systems for EDSs [4]. In [5], a conceptual framework to describe the self-healing feature of smart grid in which the self-healing feature is investigated at two primary levels including system level and component level. Herein, a set of control actions are introduced aiming at accelerating the FLISR function [5]. Accordingly, the smart EDSs will respond more quickly to the prospective component failures which improve the reliability level of the EDSs.

On the other hand, demand response (DR) programs are proposed to be executed in EDSs, thanks to the recent advances in communication infrastructures installed in the EDSs. In this regard, numerous researches have been accomplished aiming at utilizing the DR programs to improve EDSs operation [6-15]. In [6], a review on various benefits of DR programs for EDSs are comprehensively reported. In [7], DR programs was implemented for congestion management considering wind energy in deregulated power markets. Authors in [8] proposed that the distribution system operator (DSO) incorporates DR programs in order to minimize power loss payment of EDSs considering uncertainty of electricity price. In addition, the generated pollutions in the power systems are proposed to be reduced through implementing DR programs in [9]. Furthermore, DR programs are offered to be utilized to operate EDSs in a more cost-effective way in [10-12]. In [13], DR programs are contributed in the frequency control of multi-area power systems. In [14], the voltage stability of power systems is improved through implementing DR programs. In [15], DR programs are executed to achieve peak-shaving. In addition to these applications, DR programs can be implemented in service restoration program which leads to improve the reliability level of EDSs.

In this regard, several remarkable efforts have been accomplished aiming at the reliability enhancement of EDSs through augmenting the flexibility of the customers' demanded power throughout the service restoration process [16-24]. In fact, DR programs can increase the available capacity of the backup feeding path—including the backup feeder and the interrupted-restorable customers in the faulted feeder—which in turn

increment the possibility of restoring the prioritized customers. Therefore, the reliability level of EDSs can be improved through the execution of DR programs. In [16], the reliability level of the EDSs was improved by executing DR programs. In [17], the reliability level of a wind-integrated power system was enhanced through incorporating DR programs. Authors in [18] proposed DR programs to be considered in optimal electric vehicles parking lot placement problem since it leads to reduce the total cost of the planning problem. In [19], the optimal effects of DR programs on the EDSs reliability level are investigated deliberately. In [20], the reliability level of EDSs was improved by using DR programs considering customers' behavior. Authors in [21] evaluated the reliability level of EDSs through a risk-constrained stochastic framework. Herein, a probabilistic risk-constrained approach is presented for the optimal scheduling of microgrids in order to simultaneously measure the impact of DR programs on the EDSs economic and reliability issues. In [22], a stochastic approach is proposed that employs a two-objective optimization function that simultaneously minimizes the ageing of overhead lines of EDSs and maximizes the reliability level through employing the emergency-based demand response (EBDR) programs. Thus, the presented approach creates a trade-off between the reliability and ageing costs against EBDR costs. Authors in [23] presented an approach to construct a comprehensive reliability model, in order to evaluate the reliability measures and to handle the reliability performance economic risk by DR in the EDSs considering the performance-based regulation. The presented approach quantifies the dependence of the return of DR portfolios and the risk, with regard to the expected return and the conditional value-at-risk, respectively. In [24], a price-based DR is modeled to evaluate the demanded power employing an apportionment approach. A time of use – based optimization method, which considers penalty, is developed through utilizing the particle swarm optimization algorithm in order to reach the optimal value of the electricity price. Therefore, an analytical model is proposed to measure the reliability level of the power system, regarding the time of use demand response programs.

In all of the reviewed papers on reliability enhancement of electric distribution system employing DR programs ([16-24]), the distribution automation devices locations and types are considered to be installed before. Indeed, the distribution automation planning is proposed to be conducted without considering the potential benefits of employing the DR programs in service restoration. This issue causes a lower level of efficiency of DR programs incorporation in service restoration and a higher level of outage occurrence cost. Hence, in order to fill this gap, this paper is focused on presenting a comprehensive approach that considers the employment of DR

programs in service restoration while planning the distribution automation.

In this paper, the ADA is planned for an EDS considering the available potentials of DR programs. The planning problem includes the installation of protective and controllable devices in EDS in which the EBDR programs are feasible to be accomplished. The objective function of the problem consists of various costs associated with fault occurrence in EDSs including the yearly cost of customers, the annualized investment cost of control and protection devices, and the annual cost of performing EBDR programs in the service restoration process. In order to more comprehensively determine the ADA plan, various types of customers, e.g. commercial, residential, and industrial customers, are considered in the paper. To summarize, the main contributions of the paper is as follows:

- Developing an advanced distribution automation planning approach in which the emergency-based demand response programs are supposed to be employed in the service restoration process.
- Comprehensive modeling of the emergency-based demand response programs through considering the restrictions, and behavior of customers in participating in the service restoration process.

The remainder of the paper is presented as follows. The problem formulation is given in Section 2. The recommended methodology is presented in Section 3. The case study is reported in Section 4 and the conclusions are shown in Section 5.

## 2 Problem Formulation

An advanced distribution automation planning problem is introduced in this section regarding the effect of EBDR programs incorporation in the service restoration. In this section, the proposed formulation for the planning problem will be presented in detail.

### 2.1 Objective Function

The proposed planning problem determines the location of circuit-breakers, automatic switches, manual switches, and fuses as well as the EBDR programs. Therefore, the fitness function of the presented problem is formulated in expression (1). Herein,  $C^{Int}$  denotes the total yearly interruption cost, which should be paid to customers due to contingency occurrence in EDS. Besides,  $C^{DA}$  is the net present cost of distribution automation that refers to the cost of installing protective and control devices in EDS. Further,  $C^{EBDR}$  indicates the total cost of executing EBDR programs during service restoration.

$$\text{Minimize } OF = C^{Int} + C^{DA} + C^{EBDR} \quad (1)$$

The first term of the objective function is formulated in

(2), where the  $\rho_{ij}$  is the penalty rate, should be paid to customers connected to bus  $j$ , based on the value of their interrupted power in  $i$ -th year of the planning problem. In addition,  $P_{ij}$  denotes the demanded active power of consumers located at bus  $j$  in  $i$ -th year. Moreover,  $\lambda_{ki}$  indicates the failure rate of component  $k$  in  $i$ -th year of the planning period. Further,  $ot_{ijk}$  is a variable that is equal to the outage time experienced by customers connected to bus  $j$  because of fault occurrence in component  $k$  in the  $i$ -th year of the planning period. Also,  $PW_i$  is the present worth value coefficient which transfers the costs imposed to the network operator as a consequence of failure occurrence in EDSs during the  $i$ -th year of the planning problem.

$$C^{Int} = \sum_{i \in \Omega^{yr}} PW_i \left( \sum_{j \in \Omega^{LP}} \rho_{ij} P_{ij} n_j^{Cust} \sum_{k \in \Omega^{Cnt}} \lambda_{ki} ot_{ijk} \right) \quad (2)$$

The second term of the objective function is formulated in (3), where the distribution automation cost includes the investment cost and the yearly maintenance cost of installed control and protective devices, which are presented in expressions (4) and (5), respectively. In (4), the first, second, and third parts respectively refer to the investment cost of manual switches, automatic switches, and circuit-breakers installed in EDS. Moreover, the fourth part of (4) presents the investment cost of fuses. Herein, the installed fuses should be replaced upon their performance after a fault occurrence. Therefore, the fifth term of (4) should be considered in order to more deliberately calculate the total investment cost. It is worth to mention that  $\omega_i$  is a binary variable which is equal to one provided that the protective or control device installed at candidate location  $i$ , otherwise zero.

$$C^{DA} = C^{INV} + C^M \quad (3)$$

$$C^{INV} = \sum_{i \in \Omega^{MS}} \omega_i^{MS} C_i^{MS} + \sum_{i \in \Omega^{AS}} \omega_i^{AS} C_i^{AS} + \sum_{i \in \Omega^{CB}} \omega_i^{CB} C_i^{CB} + \sum_{i \in \Omega^F} \omega_i^F C_i^F + \sum_{j \in \Omega^{yr}} PW_j \sum_{i \in \Omega^F} \omega_i^F C_i^F \lambda_{ij} \quad (4)$$

The maintenance cost of installed protective and controllable devices is computed as presented in expression (5), where  $C_{ij}^m$  denotes the maintenance cost of device  $j$  in the  $i$ -th year.

$$C^M = \sum_{i \in \Omega^{yr}} PW_i \left( \sum_{j \in \Omega^{DB}} C_{ij}^m \right) \quad (5)$$

The third part of the objective function is formulated in (6). Herein,  $\rho_{ij}^{inc}$  is the incentive rate of participation, which is paid to customers located at load point  $j$  proportional to the amount of their shed power—i.e., the power which is shed by the outage management system during service restoration based on a pre-signed demand response contract- in  $i$ -th year.  $P_{ijk}^{RD}$  denotes the amount

of demand can be reduced by the customers located at bus  $j$  in case of failure occurrence in component  $k$  during the  $i$ -th year of the planning problem. Further,  $pdt_{ijk}$  is a variable which equals to the contribution duration of customers connected to load point  $j$  during the restoration process after failure occurrence in component  $k$  in the  $i$ -th year of the planning period.

$$C^{EBDR} = \sum_{i \in \Omega^{yr}} PW_i \left( \sum_{j \in \Omega^{LP}} \rho_{ij}^{inc} \sum_{k \in \Omega^{Cnt}} P_{ijk}^{RD} \lambda_{ki} pdt_{ijk} \right) \quad (6)$$

## 2.2 Problem Constraints

The introduced planning problem possesses several restrictions that are presented in this section.

### 2.2.1 Electric Distribution System Constraints

EDSs possess several operational constraints which should be taken into account in the planning problems. Therefore, these constraints are formulated below:

- **Voltage Level**

The voltage level of buses must be ensured to be in an acceptable interval in order to preclude customers' electric appliances from being damaged by the undesirable level of voltage. Therefore, this restriction is considered in expression (7). Herein,  $V_j^{\min}$  and  $V_j^{\max}$  respectively indicate the minimum and maximum permissible voltage levels of bus  $j$ .

$$V_j^{\min} \leq V_{ijk} \leq V_j^{\max}, \quad \forall i \in \Omega^{yr}, j \in \Omega^{LP}, k \in \Omega^{Cnt}. \quad (7)$$

- **Current Level of Electric Distribution System Branches**

In order to avoid from overloading of power lines in EDS, their current level should be restricted as formulated in expression (8). Herein,  $I_j^{\min}$  and  $I_j^{\max}$  respectively denote the minimum and maximum allowable current level of power line  $j$ .

$$I_j^{\min} \leq I_{ijk} \leq I_j^{\max}, \quad \forall i \in \Omega^{yr}, j \in \Omega^{Ln}, k \in \Omega^{Cnt}. \quad (8)$$

### 2.2.2 Emergency-Based Demand Response Programs Constraints

The amounts of available power of customers that can be curtailed during service restoration are specified in contracts the customers' sign with the EDS operator. Therefore, the outage management system might have restricted access to customers' loads in case of the restoration process. Hence, these constraints are regarded in the presented problem, as formulated in expression (9).

$$0 \leq P_{ijk}^{RD} \leq P_j^{RD, \max}, \quad \forall i \in \Omega^{yr}, j \in \Omega^{LP}, k \in \Omega^{Cnt}. \quad (9)$$

### 2.2.3 Economic Constraints

Electric utilities face various economic restrictions.

Therefore, they have a limited amount of budget for distribution automation. Hence, the total cost of distribution automation should be limited as presented in (10). Herein,  $Bgt^{DA}$  denotes the amount of financial resources attributed to the distribution automation in the electric utility.

$$C^{INV} \leq Bgt^{DA} \tag{10}$$

### 2.2.4 Power Flow Constraints

In order to specify the restorable load points during the service restoration process, power balance constraints should be solved in which voltage level and current level constraint are considered as well as the performance of the installed protective and control devices. Therefore, power flow constraints are cogitated in the proposed planning problem. The power flow constraints include active and reactive power balances which are formulated in expressions (11) and (12), respectively.

$$P_{ijk}^{sub} - P_{ij} - P_{ijk}^{SD} = \sum_{l \in \Omega^{LP}} V_{ijk} V_{ilk} Y_{jl} \cos(\delta_{ijk} - \delta_{ilk} + \theta_{jl}), \tag{11}$$

$$\forall i \in \Omega^{Yr}, j \in \Omega^{LP}, k \in \Omega^{Cnt}$$

$$Q_{ijk}^{sub} - Q_{ij} = \sum_{l \in \Omega^{LP}} V_{ijk} V_{ilk} Y_{jl} \sin(\delta_{ijk} - \delta_{ilk} + \theta_{jl}), \tag{12}$$

$$\forall i \in \Omega^{Yr}, j \in \Omega^{LP}, k \in \Omega^{Cnt}$$

### 2.2.5 Reliability Indices

In addition to the economic reliability index considered in the objective function, i.e.,  $C^{Int}$ , tracking the other reliability indices would be very beneficial since it will more clearly demonstrate the effectiveness of the proposed ADA planning on the self-healing feature of the smart grid. These reliability indices include the system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), and average energy not supplied index (AENS) which are formulated in expressions (13), (14), and (15), respectively.

$$SAIDI = \frac{\sum_{k \in \Omega^{Yr}} \sum_{i \in \Omega^{LP}} \sum_{j \in \Omega^{Cnt}} n_i \lambda_{jk} P_{ik} ot_{ijk}}{\sum_{k \in \Omega^{Yr}} \sum_{i \in \Omega^{LP}} n_{jk}^{Cust}} \tag{13}$$

$$SAIFI = \frac{\sum_{k \in \Omega^{Yr}} \sum_{i \in \Omega^{LP}} \sum_{j \in \Omega^{Cnt}} n_{ik} \lambda_{jk}}{\sum_{k \in \Omega^{Yr}} \sum_{i \in \Omega^{LP}} n_{jk}^{Cust}} \tag{14}$$

$$AENS = \frac{\sum_{k \in \Omega^{Yr}} \sum_{i \in \Omega^{LP}} \sum_{j \in \Omega^{Cnt}} \lambda_{jk} P_{ik} ot_{ijk}}{\sum_{k \in \Omega^{Yr}} \sum_{i \in \Omega^{LP}} n_{jk}^{Cust}} \tag{15}$$

## 3 Solution Approach

The presented planning problem is formulated as a

mixed-integer non-linear optimization program (MINLP). In fact, the proposed MINLP problem is regarded as a knapsack problem, which should be solved by the evolutionary algorithms in order to ensure reaching optimal solutions even for real-scale EDSs [25]. Therefore, a genetic algorithm (GA) is selected in this paper to solve the proposed optimization problem. The flowchart of the introduced approach is shown in Fig. 1. As presented in this figure, firstly, an initial population—i.e., is the initial values of EBDRs and the initial locations of protective and control devices—is generated in the GA algorithm. Afterward, for each component failure the values of outage time ( $ot$ ), reduced power of contracted customers ( $P^{RD}$ ) as well as their participation duration time ( $pdt$ ) within the service restoration period are determined through conducting power flow studies. It is worth mentioning that, the MATPOWER power flow analysis is employed in this paper.

Then, the value of all parts of the fitness function involving the total customer interruption cost, the total investment cost of distribution automation, and the total cost of customers' contribution in service restoration are calculated according to  $ot$ , the initial population generated,  $pdt$  and  $P^{RD}$ , respectively. This iterative process continues until the iteration number reaches its maximum allowable value. Therefore, the value of the optimal objective function is equal to the value of the fitness function in the last allowable iteration of the optimization algorithm.

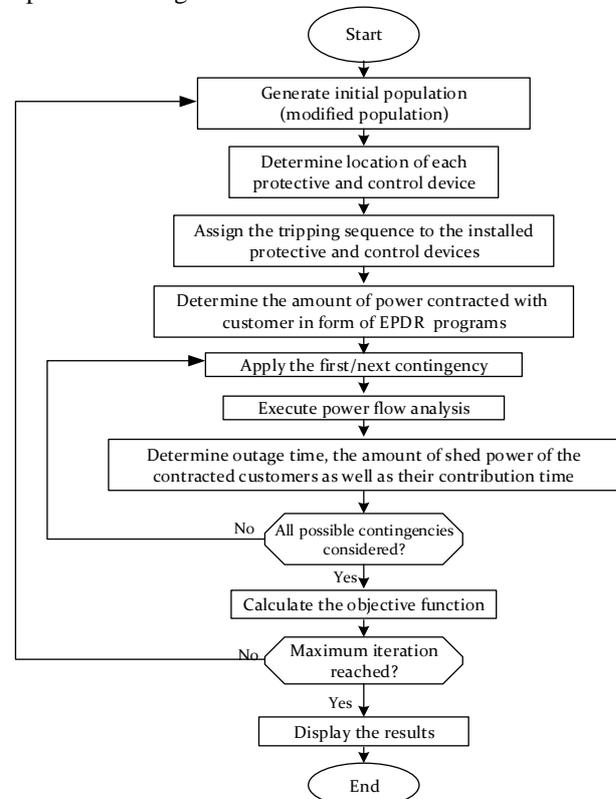


Fig. 1 The proposed flowchart for solving the proposed ADA planning problem using the GA algorithm.

## 4 Simulation Results

### 4.1 Case Study

The standard distribution test system, which is utilized to delineate the efficacy of the proposed approach, is bus number 4 of the Roy Billinton test system called RBTS4 as shown in Fig. 2. Data of the RBTS4 including failure rates, repair times, active and reactive demanded at various load points are driven from [26].

The proposed planning problem considering the available potentials of EBDR programs is implemented on bus number four of the Roy Bilinton test system (RBTS-4) [26]. This case study has three MV substations, seven MV feeders, and 29 buses. It is assumed that a circuit-breaker is installed at the first line of each feeder of the test network. In addition, each feeder is supposed to be connected to the other feeder through a normally-open tie switch, as depicted in Fig. 2. Furthermore, the failure rate and repair time of power lines in the test system are assumed to be equal to 0.065 failure per kilometer per year and three hours, respectively [26]. The lengths of power lines in RBTS4 are reported in Table 1. Moreover, failure rates of transformers and MV busses are supposed to be respectively equal to 0.001 failure per year and 0.015 failure per year [26]. In addition, the restoration periods in case of fault occurrence in the transformers and buses are about five hours and three hours, respectively. It is worth to mention that the maximum active and reactive demanded powers of each load point in RBTS4 are considered in order to more definitely demonstrate the effectiveness of regarding EBDR programs in the ADA planning problem.

Furthermore, maximum and minimum allowable voltage levels for each bus of the RBTS4 are assumed to be respectively equal to 1.05 p.u and 0.9 p.u, respectively [27]. Besides, the investment and maintenance costs of the circuit breaker, automatic switch, manual switch, and fuse are assumed to be respectively equal to 21,000 USD, 15,000 USD, 6000 USD and 170 USD [28]. Moreover, the penalty charges for different customer types are reported in Table 2 [27]. It is assumed that the electric utility attributes 350,000 USD for distribution automation. In

addition, the horizon of the proposed planning problem is assumed to be five years. It is supposed that the interest and inflation rates in the planning horizon are equal to 7% and 6%, respectively.

In addition, it is assumed that once a fault occurs, all of the called customers have declared that they can decrease up to 25 percent of their demanded power during the service restoration process. In fact, customers accept to reduce up to 25 percent of their demanded power in exchange for receiving the incentive charge which is supposed to be ten times expensive than electricity price, i.e.,  $P_j^{RD,max}$  equals to 0.25 of the demanded power of load point  $j$  and  $\rho_j^{inc,max}$  equals to ten times of the electricity price at load point  $j$ . Indeed, the customer behavior in participating in the service restoration is modeled via an S-function, as follows:

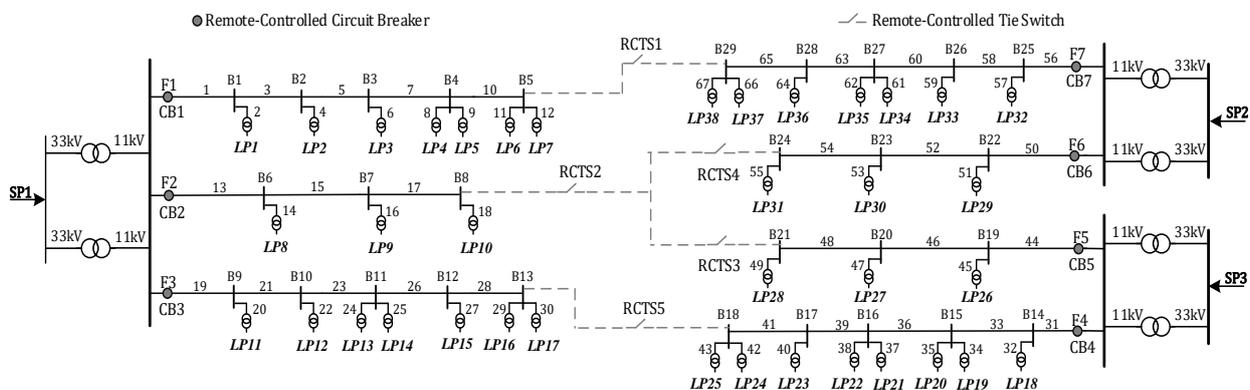
Based on the aforementioned details, the proposed planning problem is a comprehensive constrained optimization problem, which is formulated as an MINLP problem. All simulations are executed on a PC equipped with Intel 2.67-GHz CPU and 4-GB RAM using GA algorithm in MATLAB environment [29]. It is worth to mention that all of the duration time of the simulations, which are reported in this section, are less than 10 mins.

### 4.2 Results and Discussions

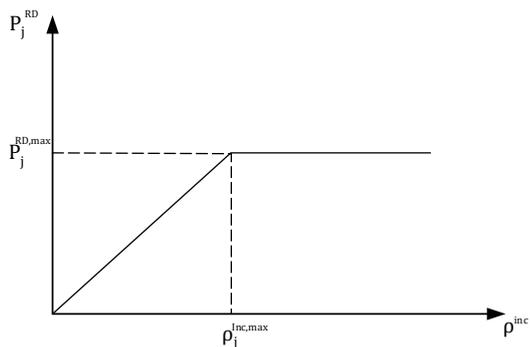
The presented planning problem that considers the possibility of employing EBDR programs during the service restoration process is solved in MATLAB software using the GA algorithm. To deliberately demonstrate the effectiveness of considering the incorporation of the demand response program in service restoration, four cases are defined as follows:

**Table 1** Line lengths for RBTS4 [26].

Length [km]	Line number
0.6	2, 6, 10, 14, 17, 21, 25, 28, 30, 34, 38, 41, 43, 46, 49, 51, 58, 62, 64, 67
0.75	1, 4, 7, 9, 12, 16, 19, 22, 24, 27, 29, 32, 35, 37, 40, 42, 45, 48, 50, 53, 56, 60, 63, 65
0.8	3, 5, 8, 11, 13, 15, 18, 20, 23, 26, 31, 33, 36, 39, 44, 47, 52, 54, 57, 59, 62, 66



**Fig. 2** Case study (RBTS4).



**Fig. 3** The considered S-function for customers' behavior in participating in the service restoration process.

**Table 2** Interruption penalty rate for various customer types [27].

Customer type	Momentary	30 Minutes	1 Hour	4 Hours
Residential	\$15.9	\$18.7	\$21.8	\$48.4
Small C & I	\$187.9	\$237.0	\$295.0	\$857.1
Medium and Large C & I	\$2.6	\$2.9	\$3.3	\$6.2

**Table 3** Results for each case.

Case	SAIFI [fr/cust.yr]	SAIDI [hr/cust.yr]	AENS [kWh/cus.yr]	$C^{int}$ [kUSD/yr]	Fit [kUSD]
1	0.687	2.962	19.569	1682.5	8413
2	0.565	1.271	8.051	478.18	2630
3	0.356	0.909	5.673	151.91	914
4	0.356	0.909	5.673	151.91	914

**Table 4** The optimal sites of protective and controllable equipment in each planning case.

Case	Optimal location of control devices		Optimal location of protective devices		Inv. [k\$]
	Automatic switch	Manual switch	Circuit breakers	Fuses	
1	-	-	-	-	-
2	7D, 13D, 21D, 29U, 31D, 35U, 41D, 51U	3D, 5D, 9U, 15D, 15U, 17U, 19U, 23D, 25D, 25U, 33D, 39D, 39U, 41U, 45D, 47D, 53D, 55U, 57D, 57U	-	All LPs	240
3	7U, 15D, 35U, 41D	13D, 13U, 15U, 21U, 23D, 25U, 29U, 33D, 39D, 41U, 45D, 47D, 47U, 55D, 57U	-	All LPs	155
4	7U, 15D, 35U, 41D	13D, 13U, 15U, 21U, 23D, 25U, 29U, 33D, 39D, 41U, 45D, 47D, 47U, 55D, 57U	-	All LPs	155

- Case 1: The existing system which is not equipped with the protective and control devices as well as EBDR programs,
- Case 2: The ADA planning—including automatic and manual switches placement in EDS—considering the effect of EBDR programs in the planning problem,
- Case 3: The ADA planning problem—including automatic switch, manual switch, and fuse placement in EDS—in which EBDR programs are employed in service restoration,
- Case 4: The ADA planning problem—including automatic switch, manual switch, fuse, and circuit breaker placement in EDS—in which the EBDR programs are incorporated in the service restoration process.

The adjusted values for parameters of the GA algorithm are as below:

- Population size: 200,
- Generation number: 300,
- Branch population: 12.

The obtained results related to each case are reported in Table 3. As presented in this table, the values of the objective function for Case 3 and Case 4 are notably lower than the other cases which demonstrate the effectiveness of the presented planning method. In addition, the other reliability indices are also improved in the third and fourth cases compared to those of the other cases that guarantee the priority of the bestowed planning problem. It is worth mentioning that the SAIFI index affects by the operation of installed fuses and

circuit breaker, however, operation of all installed protective and controllable devices, involving automatic switches, manual switches, circuit breakers, and fuses, highly impact the SAIDI index. Therefore, in the third and four cases, the SAIDI index is more reduced compared to the SAIFI index.

Furthermore, the optimal sites of the installed protective and controllable equipment are presented in Table 4 for each case. In this table, U and D denote the upstream and downstream of each power line, respectively. For instance, 7D means that a control or protective device is installed on the downstream side of power line number seven. Also, the obtained results reported in this table show that the circuit breakers are not economically justifiable to be installed in EDSs due to their high investment cost. However, fuses are selected to be installed at all candidate locations in the EDS since they significantly reduce the outage occurrence rate of customers which consequently causes a notable decline in the total interruption cost of customers.

On the other hand, the value of fitness function in the third and fourth cases is lower than that of the other cases, although the investment cost of distribution automation, in this case, is lower than the other ones. In fact, considering the available potentials of deploying EBDR programs in service restoration significantly reduces the beneficence of installing protective and control devices since incorporating EBDR programs in service restoration leads to reducing the number of high-priority interrupted customers through curtailing the

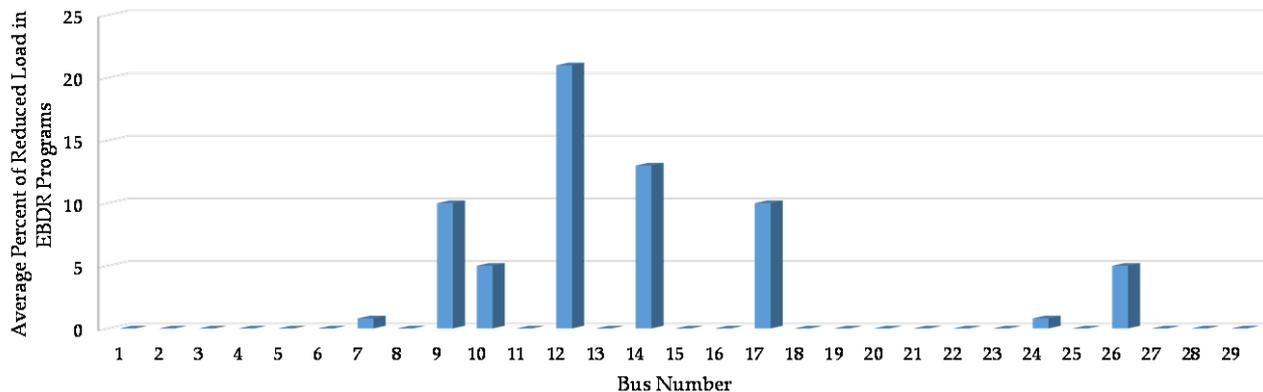


Fig. 4 Average percent of reduced load in EBDR programs.

Table 5 Obtained results of ADA planning for each case.

Case	Investment [kUSD]	$C^{int}$ [kUSD/yr]	Fit [kUSD]
Existing system	1	–	1682.5
Without considering EBDR programs	2	222	651.62
Considering EBDR programs	3	148.93	176.14
Without considering EBDR programs	4	148.93	176.14
Considering EBDR programs	2	240	478.18
Without considering EBDR programs	3	154.93	151.91
Considering EBDR programs	4	154.93	151.91

Table 6 Reliability indices for the ADA planning for each case.

Case	SAIFI [fr/cust.yr]	SAIDI [hr/cust.yr]	AENS [kWh/cus.yr]
Existing System	1	0.687	2.962
Without considering EBDR programs	2	0.687	1.56
Considering EBDR programs	3	0.331	0.968
Without considering EBDR programs	4	0.331	0.968
Considering EBDR programs	2	0.765	1.271
Without considering EBDR programs	3	0.356	0.909
Considering EBDR programs	4	0.356	0.909

demanded the power of contracted customers which have lower priority.

The mean percent of loads reduced in form of EBDR programs are shown in Fig. 4 for each bus. As reported, the contributions of LP26, LP17, LP14, LP9, and LP12 in service restoration are more than the other load points. Indeed, most of the customers connected to these buses are residential ones, which have lower values of interruption penalty charge rates and incentive charge rates, rather than those of the industrial and commercial customers. Hence, these load points are more employed in service restoration.

As presented in Table 5, considering the employment of the EDRP programs in service restoration highly affects the value of fitness function in Case 2. However, this factor has lower impacts on the third and fourth cases since installing protective devices—which is considered in the third and fourth cases—leads to preventing outage occurrence extension to the other load points in case of fault occurrence in load points at which the protective devices are installed. Therefore, the fitness function decline in the third and fourth cases in which the EBDR programs compared to the third and fourth cases which ignore the available potential of incorporating EBDR programs in service restoration is lower than that of the second case.

In addition, as reported in Table 6, SAIDI and AENS indices reduced for all cases when the EBDR programs are supposed to be incorporated in the service restoration process. However, the SAIFI index slightly increased for Case 2, Case 3, and Case 4 when the

EBDR programs are considered in ADA planning problem. In fact, incorporating EBDR programs causes to curtail more customers with lower priority to increase the restorability of customers with higher priority levels. Therefore, the SAIFI index for EBDR-based ADA planning cases is higher than ADA planning cases in which the EBDR programs ignored.

The yearly interruption costs of customers in EDS are demonstrated in Fig. 5. As shown in this figure, the customers’ interruption cost in cases with the EBDR programs are significantly lower than the cases which ignore the available potentials of EBDR programs in the ADA planning problem. In addition, the customers’ interruption cost in the third and fourth cases are notably lower than that of the first case since fuses are installed in EDS in the third and fourth cases which prevents occurred faults on laterals at which fuses are installed from being promoted to the other load points.

### 5 Conclusion

In this paper, an ADA planning problem is introduced in which the available potentials of incorporating emergency-based demand response programs in the service restoration process are considered comprehensively. The fitness function of this planning problem consists of various costs associated with fault occurrence in electric distribution systems consisting of the total yearly cost of customers’ interruptions, the total annualized investment cost of control and protection devices deployment, including sectionalizing

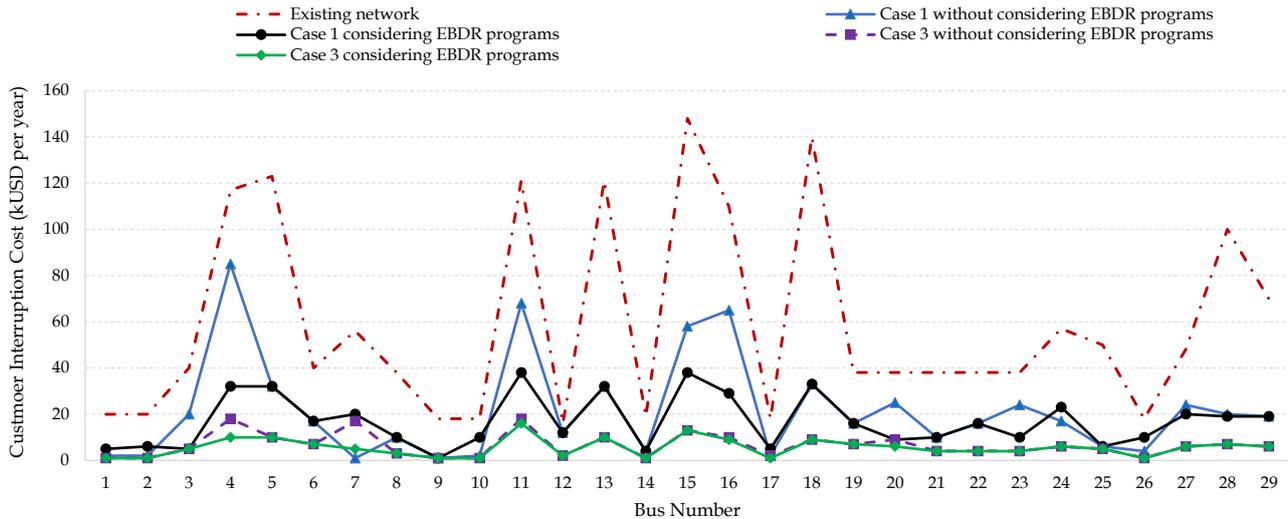


Fig. 5 Customer interruption cost for each case with and without considering the EBDR programs.

switches, circuit breakers, and fuses and the total annual cost of performing emergency-based demand response programs in the service restoration process.

The obtained results demonstrate the effectiveness of the proposed ADA problem as the fitness function of the introduced ADA problem was notably lower than studies in which the emergency-based demand response programs were not considered in the ADA planning problems.

In addition, SAIDI and AENS, as two reliability indices, were improved when the suggested ADA planning method was implemented on an EDS compared to the other ADA planning methods. Furthermore, it was observed that, in case of employing the proposed ADA planning method, the SAIFI index increased since incorporating emergency-based demand response programs causes to curtail more customers with lower priority in order to increase the restorability of customers with higher priority level.

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