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Distribution Network's Reliability Enhancement and Cost Reduction Using Multi-Objective Placement of Fault Indicators Considering the Loads Uncertainty

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Keywords

Fault indicators,
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Distribution network's Reliability,
NSGA II algorithm.

Abstract

Considering problems associated with the vastness of distribution networks, a method to confront these problems and preventing frequently occurred failures, improve network's reliability for outages. One of the effective methods of improving distribution network's reliability is the use of equipment for indicating fault location in order to rapidly locate the failure position. In the present work, the placement of fault indicators using multi-goal objective function has been accomplished which aims high reliability and low costs. On the other hand, in order to make the results as accurate as possible, system loads are considered with uncertainty and modeled using fuzzy triangular membership function. Optimizing this problem, especially for huge networks, is an intricate and difficult task which has been focused here based on the NSGAII algorithm.

1. Introduction

Generally, distribution companies use customers' reports to identify and locate the failures. By receiving problem reports from customers, the operators evaluate the failure zone using manual protection and by investigating the arrangement of the feeders. Then, to explore the area, a team should be sent to the failure area. In this method, identifying and locating the failure can be a time consuming and unsafe task. Nevertheless, in this method, not only the restoring time extremely increases but also the lifetime of the electronic equipment decreases and economic losses (due to the delay in power vending during restoring the customers network) would be inevitable for the utility. Therefore, providing a method to identify the failures, would be an appropriate guide to locate the actual failure location and to isolate the aforementioned area. This method will expedite the process of restoring the network and prolong the lifetime of the network components. Before we introduce the locating method, we will briefly explore the current available methods.

In a study by Teng et al. [1], using the automatic fault indicators, the problem of locating the fault zone in the distribution network with automation has been solved in the minimum possible time. Ho et al. [2] studied the effects of fault indicators on the indices of reliability for the distribution network. After explaining the model and necessary approaches to evaluate the reliability of the distribution network in the presence of fault indicators, the proposed model was applied to a real network, assuming a constant arrangement for the fault indicators. The problem was solved with the fuzzy immune algorithm. In a study by Falaghi et al. [3], the effects of the placement of fault indicators on the expected energy not served (EENS) and outages cost were investigated using the genetic algorithm. The different approaches to identify faults in transmission and distribution networks were studied by Cong et al. [4]. Furthermore, the privileges and shortcomings of those methods compared with each other. In a study by Jiao and Wang [5], the placement of fault indicators using the artificial immune algorithm was studied and the total cost of reliability in terms of key customers was assessed using vaccination in the immune algorithm. Tippachon and Rerkpreedapong [6] offered the methods of multi-objective optimization for the optimal placement of switches and protective devices in the distribution networks. In order to minimize the total cost and two reliability indices of SAIFI and SAIDI, the multi-objective algorithm of ant colony optimization was implemented for the mentioned concern. It was possible to optimize a feeder or the whole network with much less calculations [7]. In this study, in order to prevent the exponential increase in the computational complexity due to the vastness of the network, a special method of disintegration is used to decompose the network into small networks. Wang and Singh [8] investigated the importance

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of optimal placement of the protective devices and distributed generation units on the radial feeders in the distribution network reliability. Distributed generation units were introduced as a mean to enhance the reliability of distribution network. Silva et al. [9] presented a new method for the placement of protective and control components in the radial distribution feeders based on the algorithm of Tabu search. Kumar et al. [10] implemented the non-dominated sorting genetic algorithm-II (NSGA-II) for solving the problem of power restoring in the distribution network. Due to the presence of too many inconsistent objective functions, the act of power restoring is a multi-objective operation and the optimization task has several constraints. In order to reduce the total outage costs and investments in line switches and to improve the economic performance of the distribution network's automation system, Chen et al. [11] presented the immunization algorithm for the switch placement.

In this paper, to detect the location and number of fault indicators in the distribution network, a model is presented considering uncertainty in loads. To optimize the problem, NSGA-II algorithm is used which is a multi-objective algorithm based on the feasible solutions. Improving the reliability and minimizing the installation cost of fault indicators are the main goals of the present work.

2. Method of Operation of the Fault Indicators

A component that is installed on the conductor, can detect the magnetic field generated by the current and the electrical field generated by the voltage. This component is able to neglect the magnetic field resulted from normal current and sense only the current augmentation caused by short-circuit. Generally, a failure is accompanied by abrupt current augmentation and sharp drop in the voltage which depends on the protective devices response. The aforementioned component activates by sensing an increase in the current and by voltage interruption. It will reset by an internal timer after 1, 2 or 4 hours which can be controlled by an operator. Also, when the line gets its power back, it will be restarted.

Voltage sensor: In order to keep the component inactive in presence of voltage and provide possibility of device reset due to lack of voltage, sensing voltage is imperative. For this purpose, the electrical field around the conductor is sensed by the voltage sensor.

Current sensor: The current flow in a conductor generates a magnetic field around it which intensity of this field depends on the current magnitude and distance from the conductor, the current sensor functions based on this principle.

Figure 1 illustrates the block diagram of the device.

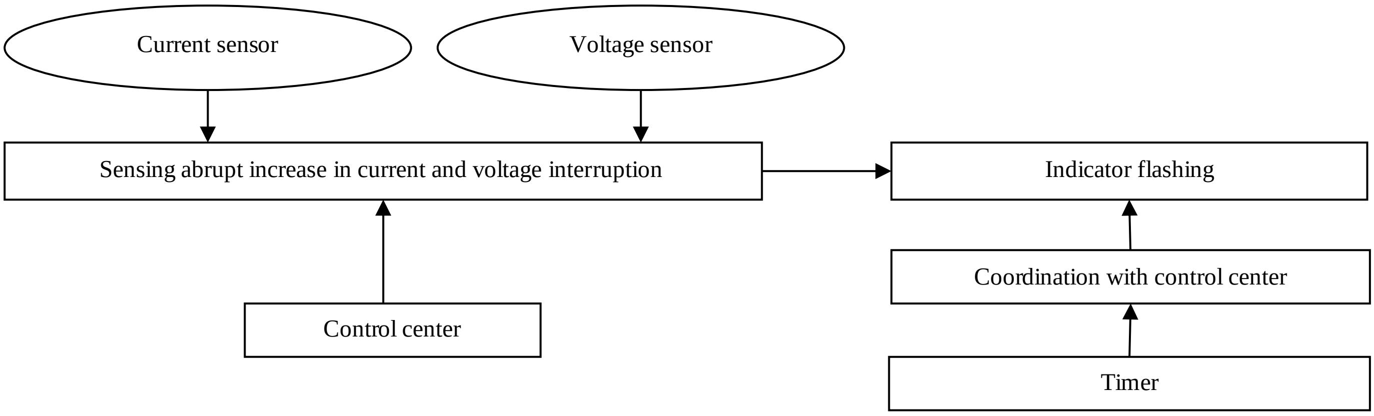

Figure 1. The block diagram of the device

3. Objective Function

In the suggested multi-goal modeling for the placement of the fault indicators in the distribution network, the objective function is considered as

$$\tilde{f}_{Total} = Min\,\{Fc, \tilde{F}_{EENS}\} \quad (1)$$

where, Fc and $\tilde{F}_{EENS}$ are the objective functions of cost and expected energy not served, respectively.

3.1. Cost Objective Function

This function is composed of two parts. Its first part is related to the installation costs and the second part refers to the costs of maintaining equipment which is a variable cost. Its present value is calculated using Eq. (3) which is a function of the interest and inflation rate.

$$F_c = \sum_{i=1}^{N_f} \gamma(i) C_{fi} + \sum_{i=1}^{N_y} \left(f_{pw}\right)^t \times \left(0.2 \times IC_{fi}\right) \quad (2)$$

$$f_{pw} = \frac{infr}{intr} \quad (3)$$

Where $\gamma(i)$ stands for the presence or absence of an indicator in the *i*th candidate location which is a value of 0 or 1. C_{fi}, N_f and N_y are the cost of each indicator installation, the number of candidate locations for the fault indicators and the target year for planning, respectively. Also, $infr$ and $intr$ correspond to the annual inflation and annual interest rates, respectively.

3.2. Function for Lack of Power or Energy Not Served

Eq. (4) is used to obtain the expected energy not served which is composed of three parts. The first part includes the lost energy during the identification of the fault and switching time. In this period, all of the loads are off. The second part includes the non-served energy for those loads that are off after switching up to the end of the repairing period. As we mentioned before, those loads have uncertainty and because of that, the function of not served energy is also in the form of a fuzzy number.

$$\tilde{F}_{EENS} = \sum_{i=1}^{N_s} L_i . \lambda_i \left[\sum_{j=1}^{N_{sw}} \tilde{P}_j T_{sw}(i) + \sum_{j=1}^{N_{rp}} \tilde{P}_j T_{rp} \right] \tag{4}$$

Here, N_s is the number of feeder branches, λ_i, annual rate of fault occurrence in the *i*th branch of feeder, L_i, length of the *i*th branch in kilometers, $T_{sw}(i)$, time to identify the fault and to switch and T_{rp} is the line repair time. Further to these, N_{sw} stands for the number of the switched off loads during the fault occurrence and N_{rp} is the number of the switched off loads which have not been restored after switching.

3.3. Time of Fault Detection and Switching

Using the fault indicators and considering their placement, the feeder is divided into several sections. Since the time to locate a fault in a section is small compared to the whole feeder, so the fault locating procedure would be quicker. In this case, the time to locate the fault is calculated from Eq. (5) as

$$T_{sw}(i) = T_0 \left[L_i / \sum_{j=1}^{N_s} L_i \right] \tag{5}$$

where, T_0 is the time to locate the fault without using fault indicators and L_i is length of the *i*th branch in kilometers.

3.4. Fuzzy Model of Load Point Power

The predicted power for each load point in every period is described in form of a fuzzy triangular number (LR) and depicted in Figure 2. Membership function of the loads are determined by Eq. (6). In this equation, m is the average load and L and R are the left and right extensions, respectively.

$$M(x) = \begin{cases} \dfrac{x-(m-L)}{L} & x \le m \\ \dfrac{(R+m)}{R} & x > m \end{cases} \tag{6}$$

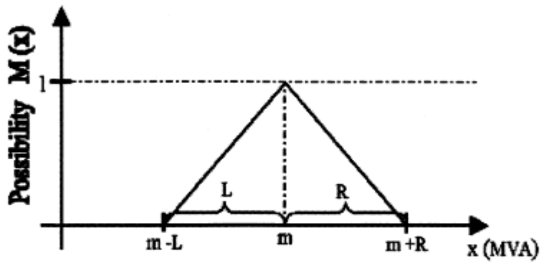

Figure 2. The fuzzy model of the load point power

4. NSGA Based Optimization

Since the genetic algorithm searches the solution space from several points in parallel, it can be used to find out a feasible subset of solutions. NSGA is a modified version of genetic algorithm that is designed to solve optimization problems with multiple measures.

4.1. Computational Stages of the Algorithm

The overall stages of NSGA algorithm for solving the optimization problems in the distribution system are as follows

1) The initial population.
2) Intersection.
3) Mutation.
4) Assessing the objective functions.
5) Classification the population based on the concept of being non-recessive.
6) Evaluating density, in this stage, considering the following index, those members who share the same non-recessive level are ranked based on the density.

$$cd(X_1) = \prod_{j=1}^{k} cd_j(X_i) \tag{7}$$

$$cd_j(X_i) = \left| \frac{f_i(X_{i+1}) - f_i(X_{i-1})}{f_j^{max} - f_j^{min}} \right|, i \in S^r \tag{8}$$

Here, $cd_j(X_i)$ is the distance of the *i*th member from the closest members on level S^r considering the *j*th objective function. The difference of f_j^{max} and f_j^{min} in the denominator of Eq. (8) shows the range which objective function f_j changes. The concept of index $cd_j(X_i)$ for a minimization problem with two objective functions is illustrated in Figure 3.

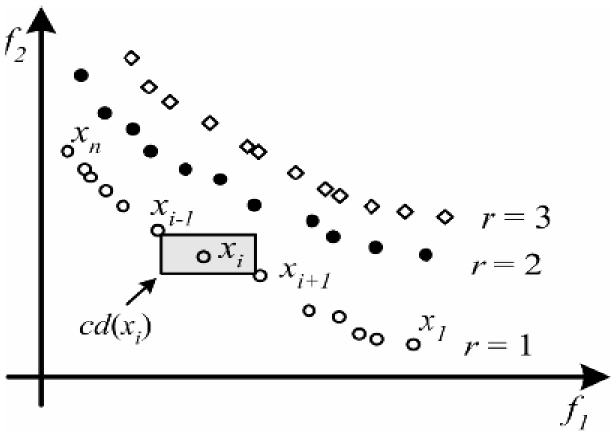

Figure 3. The visual representation of ranking and non-recessive level in a minimization problem with two objective functions

7) Selection, the proposed selection operator is based on competition and accomplished according to the following steps
Step 1: Random selection of two members from the population.

Step 2: Comparing the two selected members according to the non-recessive level r and the density index cd in such a way that if the non-recessive level of the two members were different, then the member with lower recessive level would be superior. If the two members were equal in the level, the member with lower density index would be superior.

Step 3: The superior member of the two selected members is saved in the list of the new population members.

Step 4: Those steps are repeated as much as the number of the required members in the new population.

8) Stop, the proper criteria to stop the algorithm can be a specific number of iterations or a similar one.

4.2. Decision to Choose the Final Solution

After obtaining a set of feasible solutions using NSGA, the designer should choose the final problem solution from members of this set, considering the technical priorities and the level of satisfaction. In this research, to select the best solution for the multi-objective problem, we propose the method of max-min using the following Eq. (9)

$$\max\left\{\min_k\left[\left(\frac{f_{C\,max}-R(\tilde{f}_{ck})}{f_{C\,max}-f_{C\,min}},\frac{f_{EENS\,max}-f_{EENS\,k}}{f_{EENS\,max}-f_{EENS\,min}}\right)\right]\right\} \qquad (9)$$

5. Numerical Analysis

In this paper, the placement of the fault indicators is modeled in a multi-objective form. The objective functions include: 1) the general objective function which consists of fixed and variable costs and 2) objective function for the expected energy not served. The main goal is to increase the level of system reliability and to reduce the cost of fault indicators.

In order to study and assess the presented model, performance of the algorithm and effectiveness of the proposed methodology, the primary studies have been carried out on a real network. For this purpose, the effects of adding each component on the studied system will be investigated by implementing a series of experimentations.

5.1. The Studied Network

The considered radial network is shown in Figure 4. This network has 37 buses and 72 candidate locations for installing fault indicators. Data related to the network is also given in Table 1. In this network, there are three different types of loads, i.e. residential, agricultural and industrial. Table 1 also contains the associated information with those types. The candidate locations for installing the fault indicators are shown in Figure 4. Other information related to the network are available in the appendix.

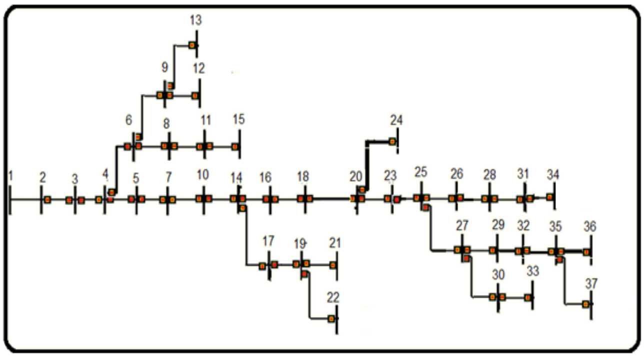

Figure 4. The candidate locations for installing the fault indicators

It should be mentioned that average cost of the lost energy for residential, agricultural and industrial loads are 850, 1300 and 1700 Rials per kilowatt, respectively.

Table 1. The general data of the studied network

Cost of installing each indicator (Rials)	25,000,000
Time to locate the fault and to switch (hours)	1
Repairing time (hours)	5
Failure rate per kilometer (f/y)	1.49
Design period (years)	5
Maintenance cost (Rials)	20% of the investment
Average cost of the residential loads (Rials)	500
Average cost of the agricultural loads (Rials)	650
Average cost of the industrial loads (Rials)	850
Annual inflation rate	0.16
Annual interest rate	0.2

In order to prove the effectiveness of the presented model in this paper, we performed two experiments on the network. In those experimentations, the effects of adding each component on the objective function will be investigated. The details of experiments are given in the following.

In the first experiment, which is system's base case, the objective function is evaluated without considering any component (Table 2). In the second experiment, the placement of fault indicators is performed and objective function values are assessed for each average cost of not supplying energy. In Table 3, fault detection and switching time in the second experiment are given. In the following tables, the results of different experiments are presented and compared.

Table 2. The results of the first experiment

Item	Value
Normalized value of cost of lost energy	1
Normalized value of cost of equipment	0
Cost of energy not supplied (defuzzied)	6890240000
Equipment cost	0

Table 3. The fault detection and switching time after installing the fault indicators in the second experiment

Section Number	Fault Detection Time	Section Number	Fault Detection Time	Section Number	Fault Detection Time
1	0.1455	13	0.1383	25	0.122
2	0.1455	14	0.1627	26	0.1101
3	0.1455	15	0.1383	27	0.1003
4	0.1455	16	0.0801	28	0.1101
5	0.1627	17	0.1383	29	0.1101
6	0.1455	18	0.0801	30	0.1003
7	0.1627	19	0.122	31	0.141
8	0.1627	20	0.0801	32	0.1101
9	0.1455	21	0.0801	33	0.1003
10	0.1627	22	0.122	34	0.141
11	0.1627	23	0.122	35	0.141
12	0.1627	24	0.122	36	0.141

Table 4. The results of the second experiment

Item	Value
Installed indicators location	4,12,15,18,25,26,30
Installed indicators cost	175000000
Maintenance and repairing cost of system	15825860
Normalized cost of energy not supplied (defuzzied)	0.7993678
Normalized value of cost of equipment	0.8125
Cost of energy not supplied (defuzzied)	6827071000
Equipment cost	1908259000

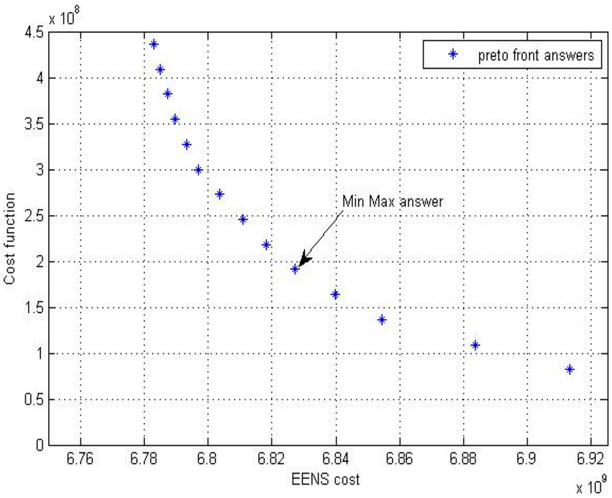

Figure 5. The feasible solution space of the second experiment

The numerical results for the best calculated solution by the method of max-min for different parts of the objective function are given in Table 4. As it can be seen from Table 4, by increasing the number of indicators, the lost energy and the cost function would decrease. On the other hand, considering the fact that by increasing the number of indicators, depending on the indicators prices, the total cost will increase, there must be an interaction between the lost energy and the total cost. From Table 3, it can be seen that, by increasing the number of indicators, the time to identify the fault in each section decreases. In Figure 5, the feasible solutions resulted by solving the problem using NSGA II and the obtained answer from the max-min method are depicted.

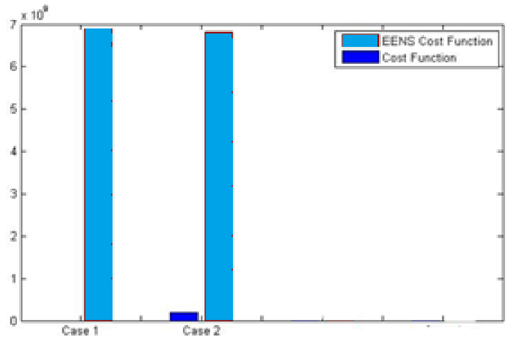

Figure 6. Comparing the results of NSGA-II algorithm obtained from different experiments

As it can be observed from Figure 6, the best solution is achieved in the second experiment. In Figs. 7-10, variations of the system reliability indices (SAIDI, CAIDI, SAIFI, EENS) resulted from installing different equipment in each experiment are compared.

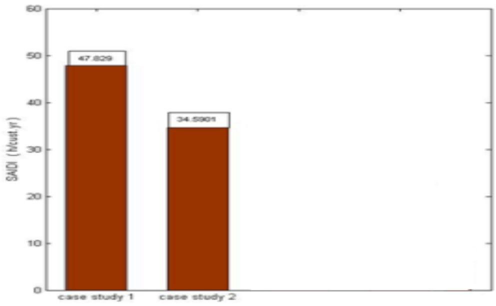

Figure 7. SAIDI results of different experiments

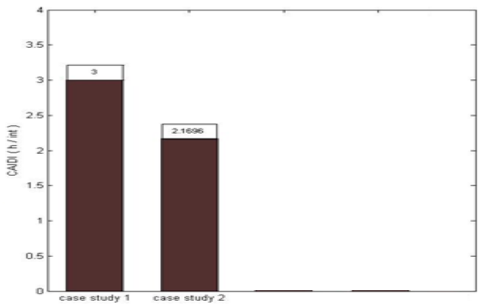

Figure 8. CAIDI results of different experiments

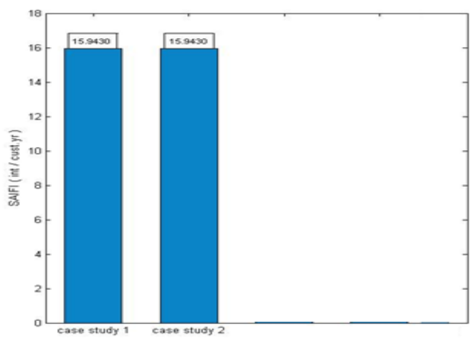

Figure 9. SAIDI results of different experiments

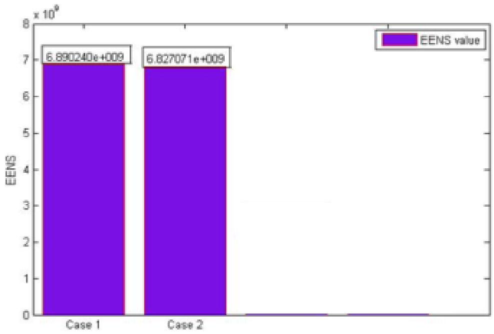

Figure 10. EENS results of different experiments

Comparing the results of the research shows that the system's average interruption duration index (SAIDI) is strongly depended on location and number of the components. This indicates that the enhancement of system reliability that is achieved by installing equipment, will be dissimilar for different components and locations.

In this research, for enhancing the system reliability, the best result was acquired from the second experiment. As it can be observed from the figures, in addition to SAIDI, customer's average interruption duration index (CAIDI) and index of expected energy not served (EENS) vary too. This is because of constant failure rate. For the same reason, CAIDI is only a function of SAIDI. Since the loads of the studied feeders are assumed to be constant, EENS is only depended on the outage period of the system. As it can be seen, SAIFI experiences no changes in all states.

6. Conclusions

Fault indicators dramatically reduce the time to locate the failures. Consequently, determining count and installation location of those indicators can intensely affect system's reliability. In the present paper, the method of NSGA-II is used to determine the optimum location of indicators. By performing different experiments, the effects of components on the cost function and system reliability indices were investigated and compared. The results provide an appropriate view point for selection procedure. Also, it showed that by multi-objective modeling using the algorithm of NSGA-II, instead of a single solution, it is possible to get a set of feasible solutions which offers a comprehensive space to the designer.

Appendices

Table A.1. The capacity of the loads connected to each bus of the studied network

Bus Number	Load Type	Predicted Load	Bus Number	Load Type	Predicted Load
2	Residential	69	20	Industrial	126.25
3	Agricultural	57.5	21	Residential	86.25
4	Residential	34.5	22	Agricultural	46
5	Residential	69	23	Residential	120.75
6	Industrial	138	24	Residential	80.5
7	Residential	40.25	25	Industrial	86.25
8	Residential	46	26	Residential	46
9	Industrial	287.5	27	Residential	97.75
10	Residential	83.95	28	Residential	124.2
11	Residential	143.75	29	Industrial	86.25
12	Residential	44.85	30	Residential	92
13	Agricultural	86.25	31	Agricultural	103.5
14	Agricultural	46	32	Agricultural	193.2
15	Agricultural	80.5	33	Residential	132.25
16	Residential	103.5	34	Industrial	138
17	Agricultural	46	35	Industrial	212.75
18	Agricultural	57.5	36	Industrial	155.25
19	Residential	86.25	37	Agricultural	181.7

Table A.2. The associated data with the sections of the studied network

Line Number	Section's initial and Terminal Buses	Section Length (km)	Line Number	Section's initial and Terminal Buses	Section Length (km)
1	1,2	0.95	19	18,20	0.7
2	2,3	0.76	20	19,21	0.9
3	3,4	1.2	21	19,22	0.42
4	4,5	1.6	22	20,23	0.92
5	4,6	0.87	23	20,24	1.16
6	5,7	0.67	24	23,25	1.25
7	6,8	1	25	25,26	1.42
8	6,9	1.35	26	25,27	0.79
9	7,10	1.32	27	26,28	0.94
10	8,11	1.09	28	27,29	1.5
11	9,12	0.43	29	27,30	1.31
12	9,13	1.43	30	28,31	1.86
13	10,14	4.5	31	29,32	1.42
14	11,15	1.1	32	30,33	1.32
15	14,16	1.34	33	31,34	1.68
16	14,17	0.56	34	32,35	1.656
17	16,18	0.34	35	35,36	1.78
18	17,19	1.7	36	36,37	1.45

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