

Improvement of Reliability Performance in Distribution Network by Optimal Investment Selection

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Abstract

Distribution system operators often face financial challenges when planning development strategies for distribution networks. These constraints affect decisions about the order and priority of maintenance tasks and the modernization of systems using equipment that incorporates new functionalities. Therefore, it is crucial to systematically and thoroughly analyze the issue and prioritize investment decisions to maximize benefits. This paper analyses the optimal distribution of limited investment funds in order to minimize the Energy not Supplied (*ENS*) indicator. The choice of investment options is made from predefined actions that include the construction of new power lines to form semi-rings, the replacement of old components with new ones, the replacement of overhead lines with underground cables, as well as installation of remotely operated disconnectors with fault indicators and installation of reclosers. Minimization of *ENS* is performed for different values of available investment funds. The optimization algorithm was developed and verified on a test system representative of a typical medium-voltage distribution network topology.

1 Introduction

The development of electric distribution network is one of the key tasks in ensuring economical, secure, and reliable electricity supply to customers. This necessitates systematic and methodical planning, which represents a fundamental business process for distribution system operators. Proper consideration of reliability indicators can contribute to better and more optimal planning of network development. Improving the distribution system should ultimately enable reliable and cost-effective power supply with enhanced power quality in the long term [1].

The introduction of the electricity market has particularly emphasized the urgent need to minimize economic losses stemming from power outages. These requirements, including the altered regulations concerning electrical energy supply, have provided the basis for defining tariffs based on reliability or penalties for distribution network operators if reliability standards are not met. According to the current regulatory models worldwide, including those in Spain or Finland, investment in enhancing system reliability is positively motivated because reliability has a direct impact on the operators' revenues [2].

Compensation to consumers for undelivered electrical energy varies and depends on the regulatory framework, laws, and practices in each country separately. In countries where it is applied, distribution system operators bear responsibility for compensating consumers if undelivered electrical energy is the result of faults in the distribution network, power outages, or lack of equipment maintenance. Improving reliability indicators is of crucial importance from the perspective of distribution system operators due to the enhancement of reputation and trust in the eyes of consumers, reduction in costs for compensating consumers, and gaining competitive advantages in the market.

Improving the reliability of distribution grids has been the subject of investigation in many studies. Paper [3] develops a comprehensive life cycle investment optimization model that incorporates planning costs, equipment renovation, and distribution automation investments to enhance the reliability of distribution networks, though it does not include a detailed optimal investment selection process focused on specific reliability indicators. Paper [4] explores various options for enhancing the reliability of rural networks by evaluating smart grid functionalities such as remote control, automation, reconfiguration, and the addition of redundant components. The study uses standard reliability indices to assess these options and identify the best approaches for improving the performance of rural networks. In [5], an optimization model was proposed with an objective function focused on minimizing the System Average Interruption Frequency Index (*SAIFI*) and Average System Interruption Frequency Index (*ASIFI*) indicators while also considering the minimization of procurement costs for protective devices, with reliability indicators treated as constraints. Expanding on this approach, multi-criteria optimization methods were introduced in [6] and [7], where the simultaneous minimization of *SAIFI*, *ASIFI*, and Momentary Average Interruption Frequency Index (*MAIFI*) was achieved through fuzzy programming. Further, [8] developed a nonlinear binary model aimed at minimizing total reliability costs, encompassing both outage costs and investments in protective devices and switches. Similarly, in [9], a nonlinear binary model was employed specifically to reduce the *SAIFI* indicator, building on previous efforts to enhance network reliability through optimized resource allocation.

The goal of this paper is to minimize the Energy Not Supplied (*ENS*) indicator while considering limited financial resources available for investment. Possible investment

options identified for the analyzed test network to reduce the *ENS* indicator include the construction of new power lines to form semi-rings, the replacement of old components (circuit breakers, disconnectors, fuses) with new ones, the replacement of overhead lines with underground cables, as well as installation of remotely operated disconnectors with fault indicators and installation of reclosers. The optimization algorithm was developed in MATLAB to solve this problem and verified on two typical distribution medium-voltage (MV) networks: semi-urban and rural networks. The paper will present the algorithm and analyze the obtained results.

2. Theoretical Framework

2.1 Reliability Indicator *ENS*

Energy not supplied (*ENS*) calculates annual energy not supplied to customers in the considered network due to long supply interruptions [10]:

$$ENS = \sum_i \lambda_i \cdot r_i \cdot N_i \cdot P_a \quad [kWh/yr] \quad , \quad (1)$$

where λ_i is the failure rate of interruption i , r_i is the reparation time of interruption i , N_i is the number of customers that lost supply during the interruption i , P_a is the average load of a customer.

2.2 Strategies for Improving Reliability Performance

In the analyzed distribution MV semi-urban and rural networks, strategies for improving reliability indicators were considered, based on the installation of new components, replacement of outdated components with new ones and upgrading both components and network operations. The analysis took into account the limited financial resources available. For each of the analyzed networks, specific investment options and the necessary funds for their implementation were defined.

The considered investment options for both analyzed networks are categorized into five groups:

1. Construction of new power lines to form semi-rings on single-fed lines;
2. Replacement of old components with new ones;
3. Replacement of overhead lines (OHL) with underground cable lines (UCL) ;
4. Installation of remotely operated disconnectors (ROD) with fault indicators; and
5. Installation of new reclosers (REC).

2.3 Component Failure Rate

The failure rate of a component is not ideally constant throughout its lifetime. The change in failure rate distinguishes three time periods: the development period, the exploitation period and the aging period. During the first period, hidden design flaws, transportation damage, assembly and installation errors and other issues come to the fore. After addressing these deficiencies, the failure rate of the component decreases and remains approximately constant over an extended period. As the component ages, it transitions into the third time period, characterized by a continuous increase in failure rate. The technical life of the component ends when the occurring fault cannot be repaired,

or when the maintenance and repair costs due to frequent failures approach the price of a new device [11].

The paper will consider the fact that there are components in the network that have entered the third time period. In the analyzed network, the age of these components will be taken into account by increasing the value of the failure rate, and as a measure to improve the network reliability indicator, the option of replacing them with new components will be considered.

2.4 The Algorithm

To calculate the *ENS* indicator, the distribution system needs to be represented using a tree structure, as this helps establish parent/child relationships between specific sections. This method of representation is convenient because it allows us to identify consumers affected by the fault, as well as the sections located before and after the observed fault location.

Below is a step-by-step description of the proposed algorithm for selecting investment options that contribute the most to reducing the *ENS* reliability indicator:

Step 1: Loading data and adopting parameters. Loading network and consumer data. Adopting average values for the failure rate and duration of component failures, as well as the time for fault localization and restoration of operational sections. Defining potential investment options and their implementation costs.

Step 2: Formation of the network tree. Constructing a network tree with parent/child relationships between specific sections.

Step 3: Calculation of the *ENS* indicator for the base case.

Step 4: Calculation of the *ENS* indicator reduction for each investment option.

Step 5: Selection of optimal investment options. Defining the optimization problem with the given constraint on total investment funds. Selecting investment options that contribute the most to reducing the *ENS* indicator.

Step 6: Results presentation and concluding the algorithm.

3 Model description

3.1 Network Models Used for Reliability Assessment

3.1.1 Distribution MV semi-urban test network (Network 1):

The scheme of the analyzed part of the semi-urban distribution system is shown in Fig. 1. It is assumed that the supply points, the normally open circuit breaker (CB), and all transformers (TRs) in the 10 kV/0.4 kV transformer stations (TSs) are ideally reliable. All lines are underground cables. All sections are of equal length, 0.3 km. A disconnector is located at both the beginning and the end of each section. The total number of TSs is 40. The number of consumers supplied by each 10kV/0.4kV TS is 60. The value of P_a is equal to 2.27 kW/customer.

3.1.2 Distribution MV rural test network (Network 2):

Consumer nodes are marked with arrows and represent 10kV/0.4kV TSs. The number of consumers supplied by each consumer node is 20. The total number of consumer nodes is 29. All lines are overhead and numbered from 1 to 49, with their lengths provided in Fig. 2. The value of P_a is equal to 2.27 kW/customer.

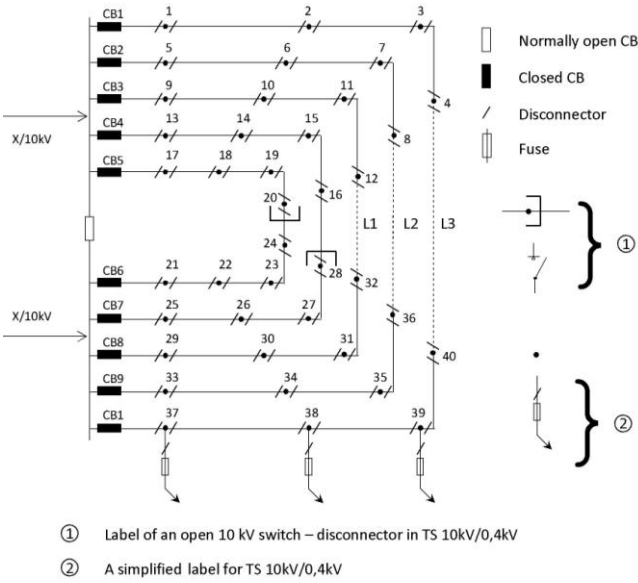


Fig. 1 Distribution MV semi-urban test network model

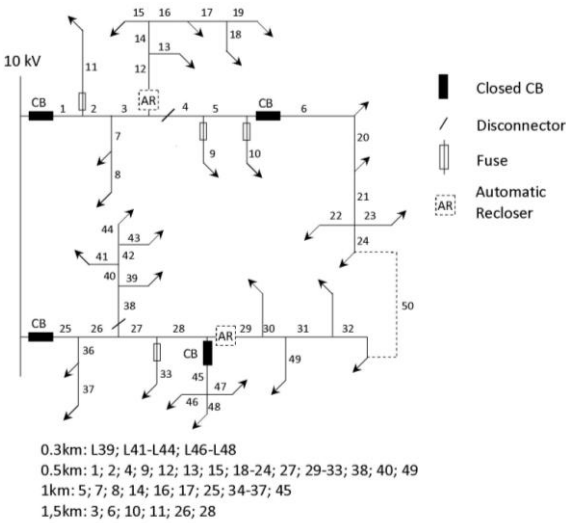


Fig. 2 Distribution MV rural test network model

3.2 Initial Reliability Data

Table 1 presents the mean values of fault rates and repair times used in this paper, sourced from Serbian DSO statistics [12].

It was assumed that the time required for fault localization and the reconnection of operational sections is $r_f=1$ h. This applies equally to the time needed for operating the switching equipment during the closure of the semi-ring and securing supply from another source.

It was specified that certain components listed in Table 2, due to their age, have a fault rate 2.5 times higher than the mean values. In Table 2, the labels are defined as follows: CB - circuit breaker, D - disconnector, F - fuse, TS - equipment in 10kV/0.4kV TS (disconnectors in line bays, and disconnector and fuse in the transformer bay).

In calculating the *ENS* indicator for both networks, faults on all initially existing equipment (lines, circuit breakers, disconnectors, fuses and reclosers) were analyzed.

Table 1 Mean values of reliability indicators of components

Components	Fault rate (faults/year)	Repair time (hours)
Circuit breaker	0.034	12
Recloser	0.034	12
Disconnector	0.0028	10.5
Fuse	0.004	2
Cable line (per km length)	0.04	20
Overhead line (per km length)	0.091	12

Table 2 Components with higher fault rates for Network 1 (semi-urban) and Network 2 (rural)

Network	Feeder / Components
1	Feeder 2: CB2, TS5, TS6, TS7, TS8
1	Feeder 5: CB5, TS17, TS18, TS19, TS20
1	Feeder 7: CB7, TS25, TS27
1	Feeder 9: CB9, TS33, TS35
2	Feeder 1: CB1, CB6, D4, F9, F10, F11
2	Feeder 2: CB25, CB45, F33

3.3 Investment Options

In the following, the strategies considered to reduce the *ENS* indicator in the analyzed semi-urban and rural networks are listed.

The strategies for the semi-urban network:

1. Construction of new power lines between nodes 12 - 32 (L1), 8 - 36 (L2), 4 - 40 (L3) to form semi-rings. It was assumed that lines L1, L2 and L3 are ideally reliable after installation.
2. Replacement of old components with new ones. Old components are listed in Table 2.
3. Installation of remotely operated disconnectors (RODs) with fault indicators in every TS on Feeder 3 and Feeder 7.

The strategies for the rural network:

1. Construction of a new power line between the ends of existing lines 24 and 32 (line L50) to form a semi-ring with the simultaneous installation of a recloser at the beginning of line L29.
2. Replacement of old components, listed in Table 2, with new ones.
3. Replacement of overhead lines L1, L2, L3, L25, L26 and L27 with underground cables.
4. Installation of a recloser at the beginning of line L12.

The analyzed investment options and the associated costs for their implementation, formed based on average market prices in Serbia, are presented in Table 3.

4 Simulation results

The minimization of the *ENS* indicator was performed for cases where the maximum available investment funds are shown in Table 4.

Table 3 Investment options and associated costs

Network	Option	Cost (€)
1	Construction of new line L1	90 000
1	Construction of new line L2	110 000
1	Construction of new line L3	100 000
2	Construction of new line L50 + Installation of recloser on L29	100 000
1, 2	Replacement of CB	8 000
1, 2	Replacement of disconnector	2 000
1, 2	Replacement of fuse	400
2	Replacement of OHL with UCL (per km)	100 000
1	Installation of ROD (per feeder)	24 000
2	Installation of recloser	10 000

Table 4 Maximum available investment funds

Case	Semi-urban network	Rural network
1	300 000 €	200 000 €
2	150 000 €	100 000 €
3	50 000 €	25 000 €
4	20 000 €	10 000 €

The reduction of the *ENS* indicator due to the implementation of the considered options for the semi-urban network is shown in Fig. 3, while for the rural network, it is presented in Fig. 4. Particular attention should be paid to the breaks in the y-axis, which enables the display of both large and small values on the same graph. The committed funds for implementing the selected options, along with the corresponding reduction in the *ENS* indicator, are presented in Table 5 for the analyzed semi-urban network and in Table 6 for the rural network.

The calculation results for both networks indicate that the construction of new lines, i.e., forming semi-rings, contributes the most to reducing the *ENS* indicator, and these options will be implemented if they fall within the range of financial resources allocated for investment. This result is justified as the formation of semi-rings enables the possibility of dual-sided supply, thus reducing the outage time for customers located on the feeder, which is now part of the semi-ring.

The results obtained for the semi-urban network show that the most significant reduction in the *ENS* indicator is

achieved through the construction of new lines L1, L2 and L3, amounting to 3591.2, 3452.7 and 3276.9 kWh/yr, respectively. Subsequent reductions in the *ENS* indicator are notably smaller, as shown in Fig. 3.

Calculations show that replacing old circuit breakers at the beginning of the feeder, especially those on feeders which form part of the semi-ring (CB5 and CB7), provides the next greatest improvement in the *ENS* indicator. This can be explained by the fact that the fault rate of CBs is higher than that of disconnectors and fuses. Replacing the CB with a new element reduces the probability of failure, thus decreasing the outage time for all customers affected by the fault.

The next greatest reduction in the *ENS* indicator is achieved by the installation of remotely operated disconnectors with fault indicators. By installing remotely operated disconnectors, quick response to network faults is enabled and the time required to isolate the faulted section of the network is reduced. Thanks to the rapid detection and isolation of faults, the outage time for end users is significantly reduced. Due to higher implementation costs, the algorithm did not prioritize these investment options, as selecting several more cost-effective solutions for the same level of investment can achieve a greater reduction in the *ENS* indicator. Subsequently, the algorithm prioritizes the disconnectors located at the beginning and end of the lines over the simultaneous replacement of fuses and disconnectors in the transformer bay of the TS, as it achieves a greater reduction in the *ENS* indicator per unit of invested capital.

The results obtained for the rural network show that the greatest reduction in the *ENS* indicator, amounting to 6616.78 kWh/yr, was achieved through the simultaneous construction of a new line and the installation of the recloser REC29. Following this, the next significant improvement was observed with the installation of the new recloser REC12, which reduced the *ENS* indicator by 2448.9 kWh/yr. The remaining reductions in the *ENS* indicator are significantly smaller, with the next reduction being more than three times lower, as shown in Fig. 4. Subsequently, the next substantial reduction in the *ENS* indicator was achieved by replacing old circuit breakers with new ones, with a greater effect when the circuit breaker is located at the beginning of the feeder.

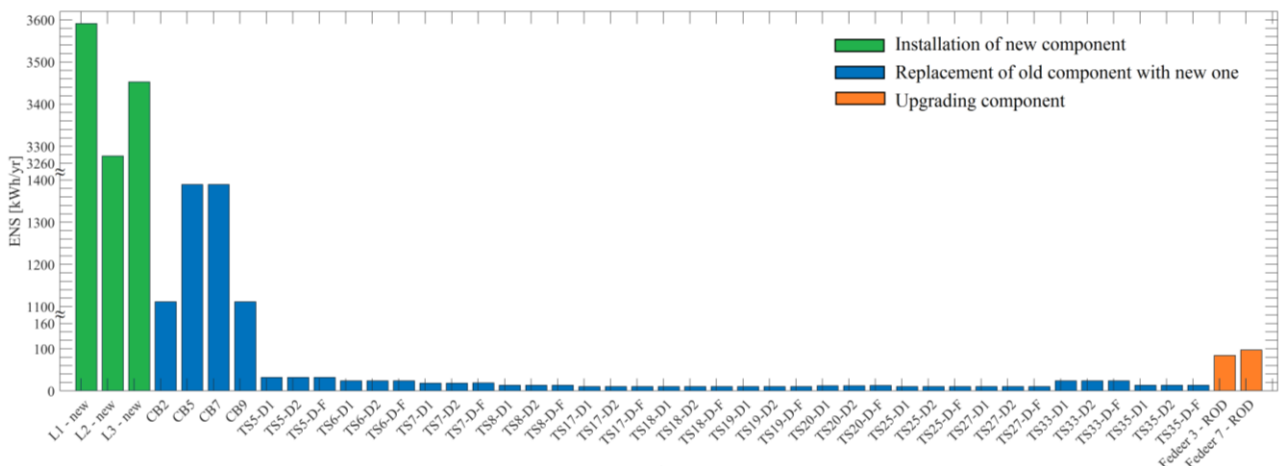


Fig. 3 Reduction of the *ENS* indicator for the considered options in semi-urban network

Table 5 Calculation results for the semi-urban network model

Max. available funds // Committed funds	Implemented options	ENS indicator in the baseline scenario [kWh/yr]	Reduction of the ENS indicator [kWh/yr]	New value of the ENS indicator [kWh/yr]
300 000 € // 298 800 €	CB2, CB5, CB7, CB9, TS5-D1, TS5-D2, TS5-D-F, TS6-D1, TS6-D2, TS6-D-F, TS7-D1, TS7-D2, TS7-D-F, TS8-D1, TS8-D2, TS8-D-F, TS17-D1, TS17-D2, TS17-D-F, TS18-D1, TS18-D2, TS18-D-F, TS19-D1, TS19-D2, TS19-D-F, TS20-D1, TS20-D2, TS20-D-F, TS25-D1, TS25-D2, TS25-D-F, TS27-D1, TS27-D2, TS27-D-F, TS33-D1, TS33-D2, TS33-D-F, TS35-D1, TS35-D2, TS35-D-F, L1-new, L3-new	18082.456	12608.306	5474.150
150 000 € // 149 600 €	CB2, CB5, CB7, CB9, TS5-D1, TS5-D2, TS5-D-F, TS6-D1, TS6-D2, TS6-D-F, TS7-D1, TS7-D2, TS7-D-F, TS8-D1, TS33-D1, TS33-D2, TS33-D-F, L1-new	18082.456	8901.487	9180.969
50 000 € // 48 800 €	CB2, CB5, CB7, CB9, TS5-D1, TS5-D2, TS5-D-F, TS6-D1, TS6-D2, TS33-D1, TS33-D2, TS33-D-F	18082.456	5217.004	12865.452
20 000 € // 20 000 €	CB5, CB7, TS5-D1, TS5-D2	18082.456	2842.221	15240.235

Legend: CB – circuit breaker, TS-D1 – disconnector in the line bay of the 10kV/0.4kV TS on the supply side, TS-D2 – disconnector in the line bay of the 10kV/0.4kV TS on the opposite side of the supply, TS-D-F – disconnector and fuse in the transformer bay of the 10kV/0.4kV TS (both components are replaced simultaneously), L – line

Table 6 Calculation results for the rural network model

Max. available funds // Committed funds	Implemented options	ENS indicator in the baseline scenario [kWh/yr]	Reduction of the ENS indicator [kWh/yr]	New value of the ENS indicator [kWh/yr]
200 000 € // 197600€	CB1, CB6, CB25, CB45, D4, D38, F9, F10, F11, F33, L1-OHL to UCL, L50+REC29-new, REC12-new	21902,867	11568,437	10334,43
100 000 € // 100 000 €	L50+REC29-new	21902,867	6616,836	15286,031
25 000 € // 23 600 €	CB1, D4, D38, F9, F10, F11, F33, REC12-new	21902,867	3323,098	18579,769
10 000 € // 10 000 €	REC12-new	21902,867	2448,876	19453,991

Legend: CB – circuit breaker, L – line, REC – recloser, D – disconnector, F – fuse

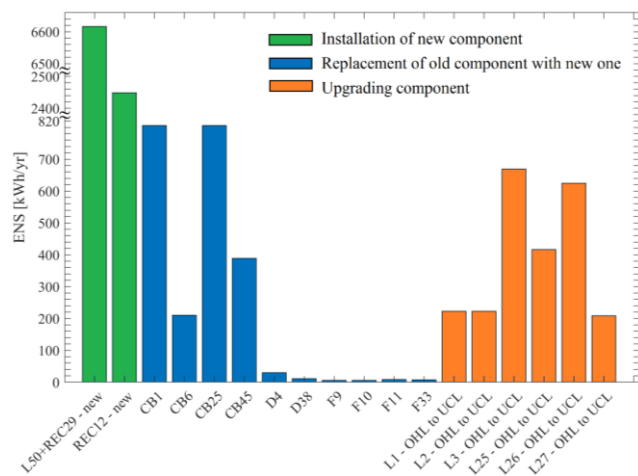


Fig. 4 Reduction of the ENS indicator for the considered options in rural network

Following this, the next in line for reducing the ENS indicator is the replacement of overhead lines with underground cable lines. Finally, the smallest reduction in the ENS indicator was observed during the replacement of old disconnectors and fuses with new ones.

As part of the analysis of the best strategies for reducing the ENS indicator in the rural network, the replacement of overhead lines with underground cables was considered. Cables exhibit a lower fault rate compared to overhead lines, which contributes to a reduction in the ENS indicator. However, due to the higher installation costs, this solution was selected only for the highest level of investment funds (Table 6). And in line with the available resources, the replacement of only one section (L1) was chosen. It should be kept in mind that, although underground cables are more expensive to install, lower maintenance costs can lead to savings by reducing expenses over time.

The graphical results of the calculations for selected investment values for the semi-urban and rural networks are presented in Fig. 5 and Fig. 6, respectively.

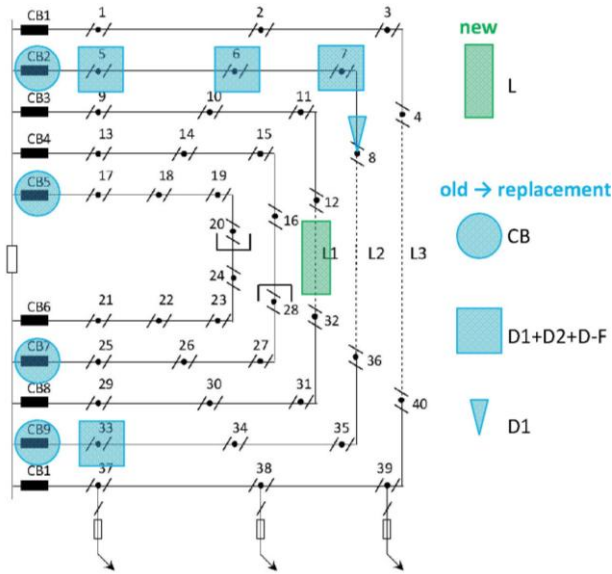


Fig. 5 Implemented options for the semi-urban network when the maximum available funds are 150 000€

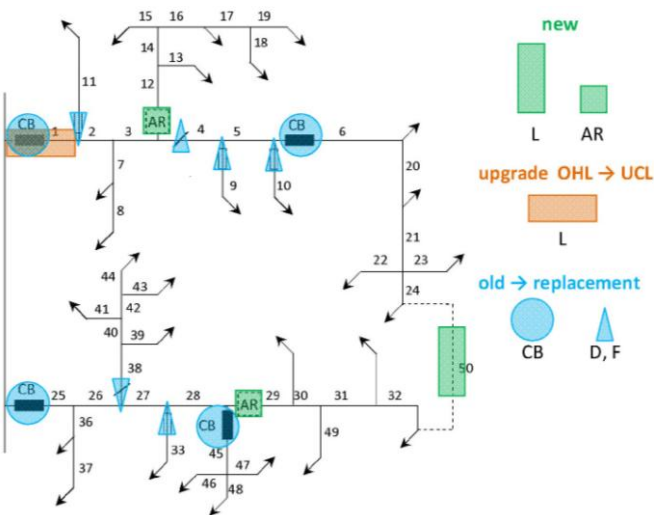


Fig. 6 Implemented options for the rural network when the maximum available funds are 200 000€

5 Conclusion

The paper presents an algorithm for the improvement of reliability performance in semi-urban and rural distribution networks by optimal investment selection. In this paper, predefined investment options that contribute the most to reducing the *ENS* indicator were selected, taking into account the limited financial resources that can be invested in the semi-urban and rural networks. The obtained results show that by applying the proposed optimization algorithm, it is possible to choose between the proposed investment options in a way that maximizes the reduction of the *ENS* indicator for the available financial resources. The calculation was carried out for simplified test systems that correspond to the typical topology of semi-urban and rural distribution

networks. The proposed optimization algorithm could also be applied to networks with more complex topologies and could consider other investment options. With a simple upgrade to the algorithm, it would be possible to analyze the expected savings due to the reduced number and duration of power outages for consumers.

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