SIMULATION METHOD FOR EVALUATION OF THE CHALLENGES IN THE RELIABILITY PERFORMANCE OF MEDIUM-VOLTAGE NETWORKS

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Abstract – High supply security is one of the key elements in the modern electricity distribution and smart grids. A reason for this is that reliable electricity distribution is almost a vital necessity for today's society. Most of the functions in the community are dependent on electricity, and if the distribution of this essential commodity is interrupted for a long time, it may cause severe damage to the customers.

This paper provides a method to assess the availability of medium-voltage (MV) networks in areas where reliability is worse than average. This makes it possible to evaluate the development of the network performance also from the perspective of worst performing sections, which can often be found for instance on long branch lines and in general on long rural-area feeders. Thus, with the presented method, the reliability investments can be focused on targets where the needs are highest.

Keywords: MV network, reliability, Monte Carlo simulation

1 INTRODUCTION

Medium-voltage (MV) networks play a significant role in considering the challenges in reliability especially in rural areas. This is caused by a high number and widespread influences of faults in the MV networks. Reliability of the electricity distribution has been traditionally measured by average interruption indices, but this aspect provides only a general view of the network. Thus, the performance of a single section of the network may be significantly worse than average, and annual variations can be substantial. Typically, the customers at the end of long branches are in difficult situation. These customers can be identified and analysed with reliability simulation. However, the large variation in fault situations during the year poses challenges to the analysis.

The weather-related faults are difficult to forecast, which is also the case with faults caused by animals and humans. The difference between these two fault types is of significance for the system reliability. Typically, weather-related interruptions can be widespread, and there can be several similar failures at the same time, for instance, because of a large storm. Hence, a prerequisite for the analysis is that there is comprehensive and accurate background information available, because simulations cannot be carried out without appropriate statistics from several years.

In this paper, the approach to the research question is based on the Monte Carlo simulation method, which is an efficient way to assess the risks in the electricity distribution and the probability of fault situations. The Monte Carlo approach is often used in the simulation of the reliability performance of power systems. Numerous studies have researched the feasibility of Monte Carlo simulation on the reliability evaluation of electricity distribution [1]–[5]. Analytical techniques have also been studied; however, if the system is complicated, it may be difficult to evaluate the probability distribution, and in some cases, it is not even possible [6].

The performance of the electricity distribution system is usually measured with traditional reliability indices such as SAIFI and SAIDI [7]. These indices provide good information on the general state of reliability in the network. However, average interruption values describe nothing from the situation of a customer, even in case where outage costs are taken into account. Hereby, the objective was to create a method that can estimate the performance of the networks and thereby provide information for the determination of the supply availability criteria, which means for instance the definition of maximum allowed values of cumulative duration of interruptions, sum of interruptions and sum momentary interruptions per year. For instance, the supply availability criteria have been determined in Finland. The illustrated analysis method is based on sequential Monte Carlo simulation, which provides an opportunity to assess the performance of the MV networks in the worst case. The simulation utilises a large amount of statistical data, which produces the fault rates and the interruption duration distribution for the modelled network. The simulation algorithm is used to model the annual customer interruptions.

2 RELIABILITY MODEL

The objective of the paper is to create a model that describes the performance of MV network from the viewpoint of single customer. This process utilises Monte Carlo simulation method to constitute the interruption analysis of the customers in electricity distribution network. The simulation process is described in Figure 1.

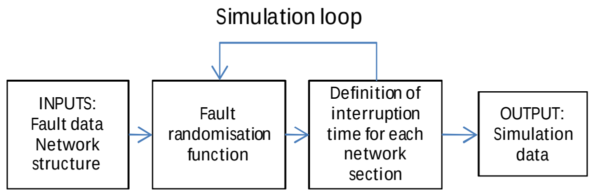

Figure 1: The principle of the simulation sequence.

The analysis system used for simulation utilises the basic data from the network information systems. This provides an opportunity to consider actual electricity networks as they are built into the environment, which is useful for the testing of the simulation method. Actual networks of a Finnish distribution company have been modelled for the simulations, which makes it possible to compare simulated results with actual measured reliability data.

In rural networks, the feeder lengths can be considerable (from 20 to over 100 km), and hence, the supply availability of the customers at different locations of the network varies significantly. Also the deviation in the interruption durations is large because of varying operating conditions. Therefore, the statistical risk analysis of the supply availability was considered necessary. Figure 2 presents simulated interruption data for a long rural-area feeder. It shows the cumulative interruption durations in the simulated artificial year that can be compared with the average interruption duration index SAIDI, which is 4.9 h/year for this feeder.

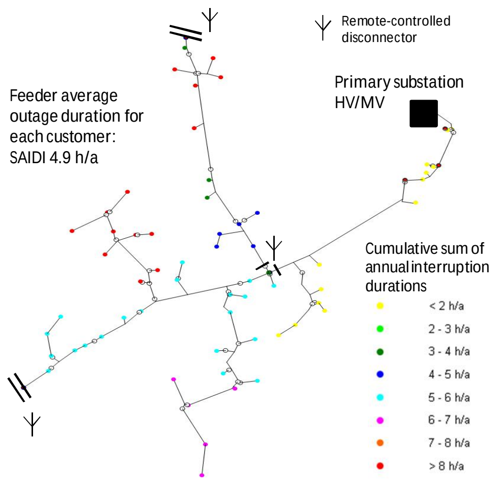

Figure 2: Simulated interruption data for a rural-area feeder and distribution-substation-based cumulative interruption durations.

The developed analysis method is based on a Monte Carlo simulation algorithm, by which it is possible to statistically assess the reliability performance of a network. The simulation algorithm is used to simulate the annual customer interruptions. The presented simulation model considers, at the moment, the fault events of the MV network, ignoring the faults in the high- and low-voltage networks. However, this does not cause significant inaccuracy to the analysis, because the MV network is in the major role when assessing the supply availability experienced by the customers on a supply area of a primary substation. When the rural distribution system is considered, by far most of the customer interruptions are caused by outages in the MV network. For instance, the interruption statistics of year 2009 in Finland show that 88% of the interruptions were caused in MV lines, 7% in secondary substations and 5% in primary substations [9].

2.1 Role of statistics

A reliable fault event simulation requires large amount of statistic data from a long period. Modern network information systems enable gathering of detailed statistics on the behaviour and operation of the distribution system in various situations. This statistical data establish the basis for probability distributions required in the stochastic analysis. Probability distributions of the fault rates of different components, switching times of disconnecting devices and fault repair times are needed in the stochastic supply availability analysis.

The first step in the initial data determination is to define fault rates for different line constructions in different operating conditions for the analysed network. First, the categorisation is done according to the outage duration (sustained or momentary). Then, the fault frequencies are divided into seven categories; overhead line in forest, roadside and field; covered conductor (CC) line in forest, roadside and field; and underground cables in general. This division is illustrated in Table 1, which includes typical fault information from a Finnish distribution network. The categorisation derives from the variation of the fault rates resulting from the different impacts of environmental conditions on the performance of different network structures that constitute the main structures in the analysed network. However, the fault rates have to be defined individually for each examined network, because the environmental conditions vary significantly. The fault rates used in this study have been defined from the data collected over the past years.

LINE TYPE	FOREST	ROAD-SIDE	OPEN SPACE
Overhead	7.7	3.6	4.1
CC line	0.68	0.33	0.2
Underground cable	0.79	0.78	0.82

Table 1: Typical fault rates [faults / 100 km,a] of different MV line types in Finland [10].

After definition of the fault rates, the next step is to evaluate the duration of the outages. The total duration of an outage caused by a fault comprises the duration of switching events to separate the faulted section of the network, the duration of the fault repair and the duration of re-energising of the faulted section. Large enough statistical outage data allow an analysis where all kinds of interruptions are represented; not only regular outages but also long ones, which can be very rare. The duration of the fault repair process typically constitutes the largest proportion of the total outage time caused by a single fault event. Also the deviation in the fault repair times is large as it is strongly affected by the cause, type and location of the fault (e.g. forest or roadside, overhead line or underground cable, amount of trees fallen on an overhead line), environmental and operational conditions (e.g. climate, number of simultaneous faults, size of the supply area) and overall operational situation of the organisation (e.g. available personnel, mobility, time of day). Figure 3 presents an example of the fault repair times in a rural overhead line distribution network. The data provide the distribution of actual faults (over 5000 fault cases within 8 years, average repair time 3 hours). From the initial data, the effects of fault location and isolation are filtered out so that the residual duration is the repair time.

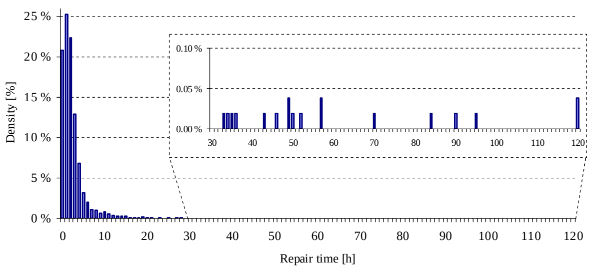

Figure 3: Density of fault repair times in a rural network based on a dataset including outage times of over 5000 fault events [11].

2.2 Customer interruptions

The locations of the disconnectors and the circuit reclosers play a key role in the determination of the customer interruptions. A detailed model of the analysed network makes it possible to allocate the interruptions to the right customers and to set the duration of an interruption into correct scale depending on the location of the switching devices.

Customer-based supply availability A gives the probability of a customer network being energised. It is commonly defined as a percentage of the year when the customer network is supplied by the distribution system, as presented in (1). Its complement is the unavailability that can be directly computed from customer-specific cumulative interruption durations $T_{\text{cumulative}}$ [2]

$$A_i = \left(1 - \frac{T_{\text{cumulative}i}}{8760}\right)\cdot 100\,[\%]\cdot \qquad (1)$$

According to (1), the supply availability can directly be described with the customer-specific cumulative time of supply unavailability. The cumulative sum of the durations of the interruptions experienced by a customer can be defined as follows

$$T_{\text{cumulative}i} = \sum_{k=1}^{K} T_{\text{int}i,k}\left[\frac{\text{hours}}{\text{year}}\right], \qquad (2)$$

where T_{int} is the interruption duration at the customer i due to section k, and K is the total amount of sections in MV network over a year. The interruption duration experienced by the customer i due to section k in the network can be defined with (3)

$$T_{\text{int}i,k} = \left(T_{\text{repair}i,k} + T_{\text{manual}i,k} + T_{\text{remote}i,k}\right) \Big/ \left(f_k \cdot l_k\right)\left[\frac{\text{hours}}{\text{interruption}}\right], \qquad (3)$$

where T_{repair} [h] denotes the sum of fault repair and reconnection time experienced by the customer, T_{manual} [h] is the time of manual isolation of the faulted section, T_{remote} [h] represents the time of remote-controlled isolation of the faulted section, f [faults/km] is the fault frequency of section k and l is the line length of section k [km]. Figure 4 presents an example where the duration of an interruption has been divided into three phases, which each contain a different number of interrupted sections and customers.

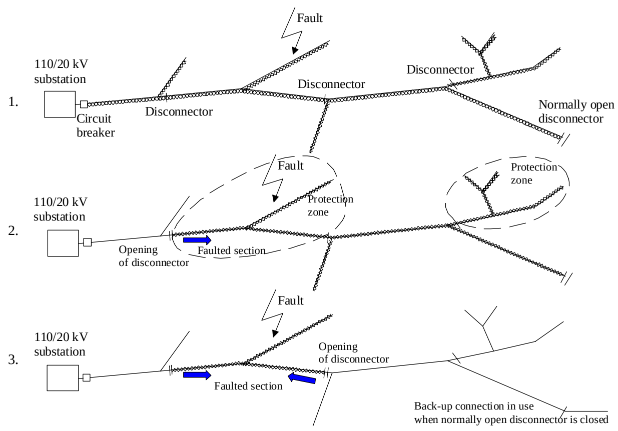

Figure 4: Fault isolation process. In the first step, the circuit breaker is operated. In the second step, the disconnector in front of the fault is opened. In the third step, the disconnector after the fault is opened and the back-up switch is closed [11].

The influences of the interruptions on the customers have been defined applying the method presented in Figure 4. The differences in the disconnector types have been taken into account in the switching times. For instance, for a remote-controlled disconnector, the switching time is only some minutes, whereas for a common disconnector it can be more than an hour.

The distributions of the fault frequencies and durations are needed to determine the cumulative durations in the certain exceeding probability. However, in the distributions uncertainty is significant that effects on results. Maximum interruption durations of the network sections are the most crucial from the supply availability criteria point of view. The maximum values can be solved by analytical or simulation method. The simulation method is chosen to be used in the study.

2.3 Weibull distribution

For the stochastic analysis, a probability distribution function is fitted to the statistical data. Both the fault repair time and fault frequencies are distributed around the mean values. The switching times of both manual and remote-controlled couplings can also be described with probability distributions. The Weibull distribution can be adapted to almost any kind of statistical data [12], and it is widely used in engineering. The Weibull distribution is selected to be used in the introduced algorithm because of its flexibility and ease of fitting to the statistical data. The equation of the Weibull cumulative distribution function is written as

$$F(x,\alpha,\beta)=1-e^{-(x/\beta)^{\alpha}} \tag{4}$$

and the Weibull probability density function

$$f(x,\alpha,\beta)=\frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{k-1} e^{-(x/\beta)^{\alpha}}\ , \tag{5}$$

where α is the shape parameter and β is the scale parameter. They can be defined with the least-squares fit from the initial data [13], [14].

For the analysis, the repair time data from the MV network are collected. It can be sorted to a form of cumulative distribution, which is also the form of the Weibull function. After fitting the cumulative form to the statistic data, it is possible to determine the Weibull probability density function (PDF). The PDF provides an opportunity to determine the probability of a fault repair time. The PDF forms the basis for the Monte Carlo simulation of the interruption durations. With the PDF, the individual durations can be allocated to the fault situations in the MV network. Figure 5 presents the PDF corresponding to the statistical data.

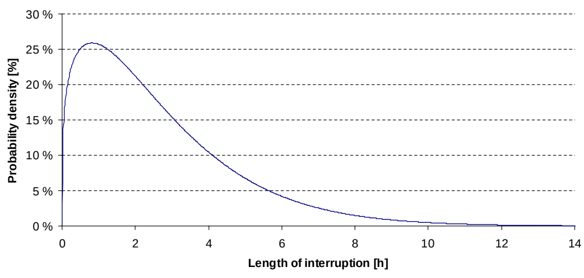

Figure 5: Weibull probability density function, based on the parameters found by fitting the statistical data that is presented in Figure 3.

If the size of the statistical data is reduced, also important information will be lost. This can be seen in the probability of long interruptions, which can be very rare. For instance, the fault statistics in Figure 3 includes long interruptions, and therefore the Weibull PDF fit has more realistic probability for long interruptions. From Figure 5 can be seen that the probability to exceed 14 hours is not big even the initial data include long interruptions also, but still there is a possibility to longer interruptions. However, if the statistical data are not large enough, the rare occurrences may not take place within the short period, which also affects the simulation process. Long repair times are due to major storms that usually happen only once in every five to ten years.

Reliable fitting of the Weibull probability distribution functions requires large statistical data sets describing several key parameters. Complete data are not necessarily available in all cases. In the Monte Carlo simulations, a lacking probability distribution function of a variable can be replaced with a constant average parameter describing the variable. However, this reduces the statistical confidence of the results, which has to be taken into account in the further analysis of the simulation results. Recognising the correct level of details in the initial data is important for reducing the calculation time and in order to deal with exhaustive statistics, yet achieving useful results.

3 MONTE CARLO SIMULATION ALGORITHM

The proposed stochastic analysis method is based on the time-domain Monte Carlo simulation algorithm. It simulates the functioning of the electricity distribution network by randomising event occurrences within boundaries defined by the probability density functions of the initial parameters. The target is to produce the customer-specific probability distributions for the cumulative duration of the sustained interruptions and for the number of momentary interruptions.

In this study, the sequential Monte Carlo method has been chosen for the basis of the stochastic model. Sequential simulation attempts to model the fault events just as they occur in actual networks. The simulation sequence, typically a year, is formed by random events building upon each other over the time. The simulation sequence is divided into small time slices to increase the accuracy of the simulation. The accuracy increases as time slices become smaller, but at the same time computation time increases. For instance, modelling of a year can be carried out with a one-hour resolution by dividing it into 8760 time slices [2]. Figure 6 presents the principle of slicing the upper-level simulation sequence into smaller pieces in the time domain.

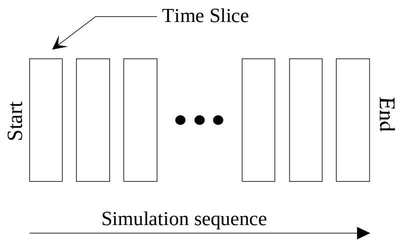

Figure 6: Time slices in the sequential Monte Carlo simulation [2].

In addition to the time domain slicing, the network comprises hundreds of sections linking the nodes of the network together. All the section ns have an expected fault rate, probability of outage duration and other individual properties of their own. Simulating the fault occurrences section by section increases the accuracy of the results. For each section and time slice, the number and duration of fault events is randomised independently. Fault events are not mutually exclusive in this kind of a simulation, enabling simultaneous fault occurrences. The variation of fault rates or repair times over a year is not considered, which is one of the development needs of the proposed model for the future. Figure 7 presents a simulation sequence for MV networks. The simulation sequence uses fault statistics and network topology to form the fault data of the system.

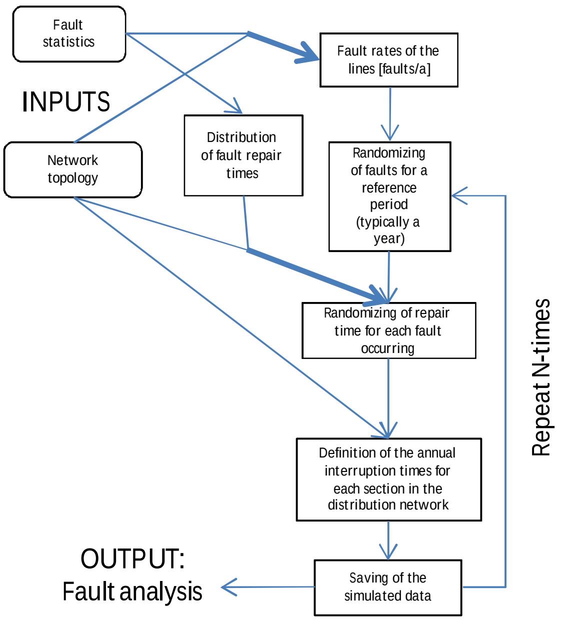

Figure 7: Fault simulation sequence of the MV network. One loop in the simulation corresponds to a year.

In the Monte Carlo simulation, a large number of simulation sequences are carried out, which all correspond to a year. These simulated years form an artificial interruption statistics for each customer in the simulated network. The algorithm used for randomising the faults for each section of the network and time slice is presented in Figure 8. All the time slices for a selected section of the network are simulated consecutively, followed by the simulations for the next section of the network and so forth, until all the sections have been gone through for a simulated year. For the following artificial years, the randomising of the faults has to be performed again so that the full simulation process is completed.

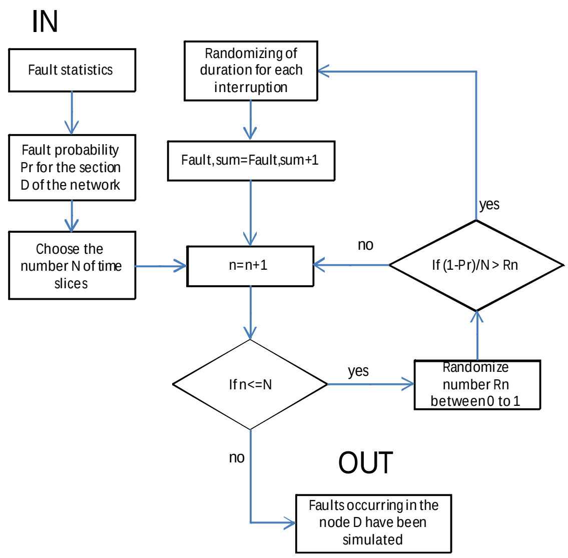

Figure 8: Fault randomising algorithm.

As can be observed in Figure 7, fault repair times can be determined after the fault randomising. This is illustrated in Figure 9 where the repair time algorithm provides the individual repair time for each simulated fault utilising the presented Weibull PDF from Figure 5 as the distribution of repair times. In addition, for the total duration of the interruption, the distribution of switching and fault location times has to be defined. For simplification, it is assumed in this study that these parameters are constant, which slightly levels out the total duration.

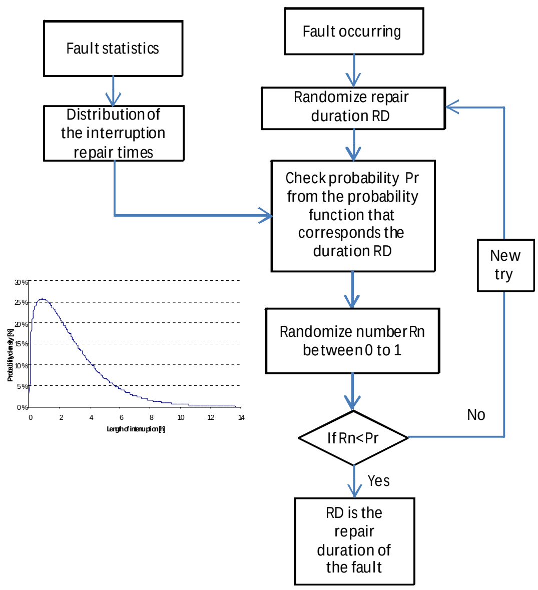

Figure 9: Fault repair time algorithm for each fault occurrence.

The presented simulation algorithm is repeated as many times as complete annual simulations are needed to achieve a large enough statistical basis for further analysis. The selection of the required number of rounds is based on the convergence of the mean (expected) value of the simulation results, that is, the difference in the mean values of two successive sets of simulations.

4 SYSTEM PERFORMANCE

Supply availability criteria are one of the motivators to evaluate the system performance from the single customer point of view. The criteria set limits for annual interruption duration and sum of both long and short interruptions. For instance, for rural areas, the limitation is set to six hours, which means that if the limitation is exceeded twice within the three-year control period, there will be some consequences.

The definition of average reliability indices does not describe the performance of the network from the viewpoint of the customers. The customers at the end of the feeder are in worse situation than the customers at the beginning of the feeder. Thus, this generates a demand to evaluate the performance of the distribution system, because all sections in the network may not meet the requirements as well as they should.

4.1 Analysed network

The analysis is based on an actual network infrastructure in a Finnish rural-area distribution company. The studied network consists of six medium-voltage feeders, which have over 2000 customers and almost 400 distribution substations. The line length is about 550 km, and the average age of the MV network is 32 years. 74% of the lines are located in forests, 10% in open-space conditions and 15% by the roadsides. The network contains almost 300 disconnectors, 24 of which are remote controlled. The network has several normally open points, which can be used for back-up supply, but there are also large areas that have no back-up connection.

4.2 Simulations

The case network is analysed by simulating the fault situations. The simulation consists of 4000 loops that all represent a year in the analysis. Figure 10 presents Monte Carlo simulation data that show the cumulative annual interruption duration curve based on the simulation and exceeding probability (EP) of a certain duration experienced by customers of a secondary substation. It shows that approximately 13% of the simulated years exceed the six hour limitation. To improve the supply availability of these customers during the worst years, significant investments in the network infrastructure may be required. In addition, some reliability investments that are beneficial from the viewpoint of general reliability do not have any positive effect on these specific customers.

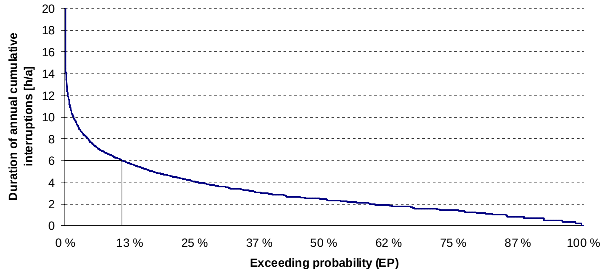

Figure 10: Simulated annual durations of interruptions experienced by customers of a challenging secondary substation.

A similar assessment is carried out for all the substations, which produces the analysis of the whole distribution network. Here, it is possible to assess the substations or the network sections where reliability poses the major challenge. Figure 11 presents cumulative interruption duration of the evaluated network with three different exceeding probabilities (EPs) that are EP 5%, EP 25% and EP 50%. It shows that even though the cumulative duration of the average year is under four hours/year with all the substations, the performance of the network during the year of very poor reliability is considerably lower. However, the year of poor reliability can be different for different substations.

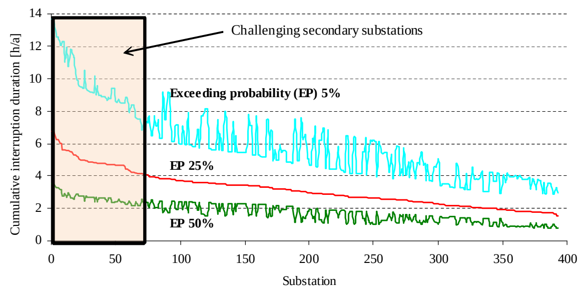

Figure 11: Cumulative interruption time of the customers in the analysed network in the present situation.

The curve of (EP 5%) in Figure 11 represents the year when customers experience long interruptions. For instance, it can be seen that in the most challenging network sections, the cumulative interruption duration can be over 14 hours/year. Naturally, the objective is to avoid years of very long interruption times. The figure shows the substations in which the probability to experience long interruptions is the highest. In the figure, 70 challenging substations that experience the most interruptions are outlined (shaded box), and they should be taken into account in the network planning to decrease the cumulative interruption durations of the substations. Hence, the simulation of the present situation can be used as a reference level for the future networks. Thus, the simulation method provides a good option to evaluate the performance of the MV network as can be observed from the case of long interruptions.

The analysis makes it possible to find the methods that increase reliability in the network especially from the perspective of the substations with the worst reliability. Figure 12 illustrates the situation of the network after a renovation process, which has concentrated on the network near the substations at the end of the branch lines, and also a couple of back-up connections have been established into sections where the most critical substations are located. These actions significantly increase the supply security.

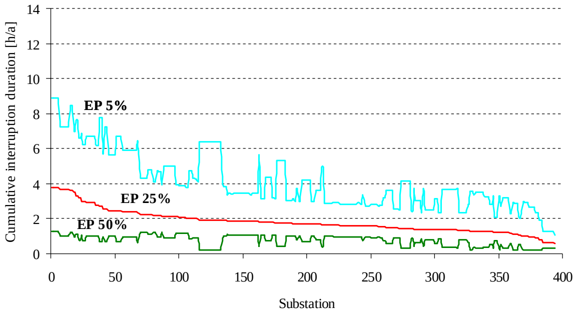

Figure 12: Cumulative interruption time of the customers in the analysed network after the development actions.

Figure 12 shows that the cumulative duration of the interruptions is significantly reduced with the renovation investments planned to the present network. The highest values in the renovated network are around 9 hours/year with the same probability level (EP 5%) that provided almost14 hours/year for the present network, which means a 35% reduction into annual interruption duration. Further, it can be seen that the interruption durations of EP 5% have decreased in general. Hence, the reduction in the cumulative interruption duration in the worst-behaving network sections is considerable, which would be a good start for the network development. The next step can be a further analysis and development proposition of the network areas where the risk of long annual interruption durations is the highest.

5 CONCLUSIONS

Monte Carlo simulation is a suitable method to consider the reliability and assess the risks of electricity distribution from the stochastic perspective. The illustrated medium-voltage network analysis method is based on sequential Monte Carlo simulation, which provides an opportunity to assess the performance of the MV networks in the worst case. The paper presents algorithms to carry out the simulation process from the gathering of statistical data to the simulation results from the fault simulation and adjustment of the durations of the network failures.

The developed algorithm is suitable for all network topologies, but especially for rural-area networks with long branch lines because typically these areas are most vulnerable to experience long interruptions. The methodology defines the areas that face the most challenges with the reliability of supply. Thus, it can be used as an analysis tool to measure the effects of development actions on the reliability of the network, with special reference to the worst-performing parts of the network.

In the future, the simulation model should be developed by including the variation of switching and fault location times into the algorithm considering the correlation between the distributions of the different time components and fault location.

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