

Optimization of Switch Allocation in Power Distribution Systems

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Abstract

The electric power system with its generation, as well as its transmission and distribution networks, is one of the most complex technical systems that humanity has created. A special concern pertains to the distribution networks on which most failures occur. Improved reliability can be obtained by increased investments, reinvestments and maintenance. The goal of this study is to examine the impact of components failure on distribution reliability. The paper describes a fault restoration sequence and duration in a distribution system and interruptions frequency and duration for different components and a development procedure for simulation after a fault and calculating associated time-varying failure rates and reliability indices and customers' outage costs. The approach minimizes the costs of allocation and energy not supplied, under reliability constraints. The simulation is based on genetic algorithm concept. Case studies with a several network configurations and real-world scenarios were used to evaluate the methodology.

Keywords

Availability, maintenance, modelling, reliability of power system

I. INTRODUCTION

Power supply process from producer to consumers, under electricity market conditions is very complex process, which continuously provides numbers of participants. The distribution of electric energy is a significant link in the whole process of power supply to consumers, which provides:

- common distribution network service;
- appropriate power supply according with quality and standards requirements in distribution network and for important consumers;

- distribution network reliability, taking into an account electricity market conditions and environmental requirements;
- power supply reliability, consisting of reliable functioning of power supply schemes and reliable equipment maintenance.

In distribution networks a fault of one of the network components causes the outage of all consumers belonging to the protection area of the feeder. Restoration of supply is performed by repeated sequences of fault location and switching actions executed by the staff. The fault action results on the identification of the not involved area and its isolation followed by switching actions for partial customer restoration. In that way the extent of the faulted feeder area is step by step reduced until fault is found and power supply is restored for customers who are not connected to faulted area [1].

This paper presents the optimization of location of power switches in distribution system.

To receive plausible results, an analysis of distribution system outages, causes, duration and future tendencies is performed.

Distribution system operator needs to balance investments aimed at improving reliability performance and performance during adverse weather conditions. Typical indicators set by Regulator are: System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). Analyzing the performance of these indicators may allow increasing return of investments and evaluating amount of outage compensations. Investments aimed at improving SAIDI and SAIFI may have limited effect on performance during severe weather conditions. Urban area reliability improvement risk management approaches are not focusing on mean values of reliability but rather on risks of long and wide-spread outages, identifying main risks, e.g., situation that can

lead to outages > 2 MW and/or duration > 6 hrs, estimating

Various simulation methods have been proposed to address the switch allocation problem, such as genetic algorithms [4], [4], evolutionary algorithms [5], simulated annealing [3], particle swarm optimization [4], ant colony optimization [6], and other specialized methods [7]. An exact dynamic programming algorithm [8] has also been proposed to solve the switch allocation problem. With respect to a global optimization, in which the entire network is optimized, the applicability of these methodologies is limited to small-scale networks, of at most 123 nodes [3].

This paper proposes a simulation based on Monte Carlo simulation and genetic algorithm with data structures suitably selected to allow for the search of solutions for different type of network configuration and customer and network data. The case studies, described below, explore decision scenarios for improving reliability of different types of network.

II. PROBLEM FORMULATION

A. Failure rates and outage process

Traditionally, failure rates have been treated as constant in most reliability studies. A constant failure rate means that the time to outage (TTO) will have an exponential distribution [9]. It seems that constant failure rates are a reasonable approximation to the actual failure of the components. However, utilities' experience has shown that most components follow a certain pattern in their life cycle. This pattern is not one of constant failure rates, but of time-varying failure rates [10]. The components in a distribution system, such as lines, cables, transformers and power switches, are usually modelled as either operating or not operating due to outage. The Time to Outage (TTO) for a component is the time until an outage occurs, and the component is no longer operable. The time until a broken component is available again, is the time it takes for it to automatic and manual switching (TTA) or to be replaced or repaired (TTR) (Fig. 1.) [11].

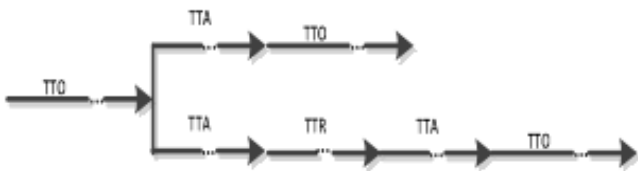


Fig. 1. The outage process of the component

B. Interruption analysis

The main causes indicate that a significant part of interruptions could be reduced by adopting new network techniques instead of using traditional overhead lines, which are the dominant structure in the distribution system and account for over 90 % of the total customer-experienced interruption time [11].

probability of these events.

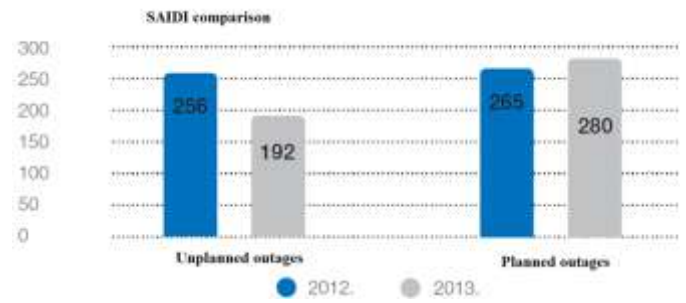


Fig. 2. SAIDI in Latvian distribution network in 2012 and 2013

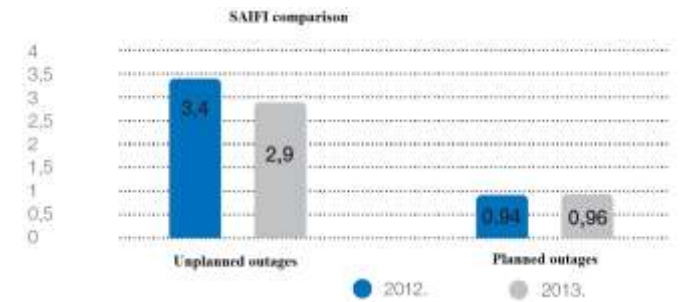


Fig. 3. SAIFI in Latvian distribution network in 2012 and 2013

Customers' interruptions are caused by a wide range of phenomena including equipment failure, animals, trees, severe weather and human error. These causes are at the root of distribution reliability, and understanding them allows abstract topics like reliability, and understanding them from a practical perspective. Equipment failures and trees falling on lines are almost always the major causes of interruptions on distribution system. In Latvian Distribution network SAIDI and SAIFI are higher compared with other European Countries due to fewer substations with medium voltage outputs and significantly longer medium voltage lines (Fig.2. and Fig. 3) [10].

Interruption analyses in Latvia were performed taking in an account interruption statistics of 3 years in normal weather conditions (Table I).

TABLE I. FAILURES FREQUENCY AND DURATION IN LATVIAN 20KV DISTRIBUTION SYSTEM

	Duration, h	Frequency, 1/year
Switches (per pcs.)	3.22	0.0048
Overhead lines (per km)	4.12	0.0935
Power switches (per pcs.)	1.74	0.0440
Cable lines (per km)	0.52	0.0217
20/04kV substations and components in substations (per pcs.)	5.19	0.1038

C. Customers' outage costs estimation

Customers' outage costs estimation has origins in early 1950s. In the first estimations two indicators were used – connected power and energy not supplied.

Customer reliability indices such as interruption frequency, interruption duration, not supplied energy and interruption cost are dependent on network structure, switching devices, information and protection equipment, the possibility of switching and emergency supply and on post fault management. For reduction of interruption duration automatic and remote control equipment control level is promoted, that

provide the rapid electric supply restore of involved customers where it helps to improve electric supply restore time.

The cost of electrical power supply is depended not only on network structure, reliable power supply level and customers groups and load demand structure, but also on regional electrical power demand and gross domestic product (GDP). The power demand level, the customer turnover, GDP, climatic conditions, customer group's structure, distribution network operator technical resources, network configuration, network automation level, distribution system operator (DSO) customer service and DSO capital investments have taken into account [1].

Prevention of customers' outage costs are divided into direct and indirect costs with economic and social impact on society. Direct costs are costs directly related to the energy not supplied which can be applied to not public customers. Indirect costs are costs not directly associated to outage but they are associated with consequences. Indirect costs can be applied to public customers. Indirect costs are losses, which from the point of causality has incurred several simultaneously running for one or other of the following causes affecting [16].

There are several customers' outage costs evaluation methods due to interruptions duration, customers' types, costs evaluation methods, data collection methods etc. reliability indices estimation methods [17]. Estimation of customers' outage costs can be divided into analytical, simulation and customers' survey methods [16, 2].

When a failure occurs in a distribution system, the system usually experiences a series of processes of fault isolation, determination of faulted area, decision making for the service restoration, switching and repairing/replacing actions. Restoration times for load points after a failure may be different due to the failure location, the number and type of switches involved, and the available power for the restoration and the switching sequences. Some load points can be restored using remote control, whereas some may require manual switching actions and others may wait until the failure component is repaired or replaced by spare elements. Some load points may require more switching actions than others, which depends on the system configuration and the fault location. The duration of switching and repairing actions depends on the degree of system automation and available switching resources. Even for the same customers, the interruption time changes depending on the location of the failure [10, 11].

D. Restoration sequence and duration

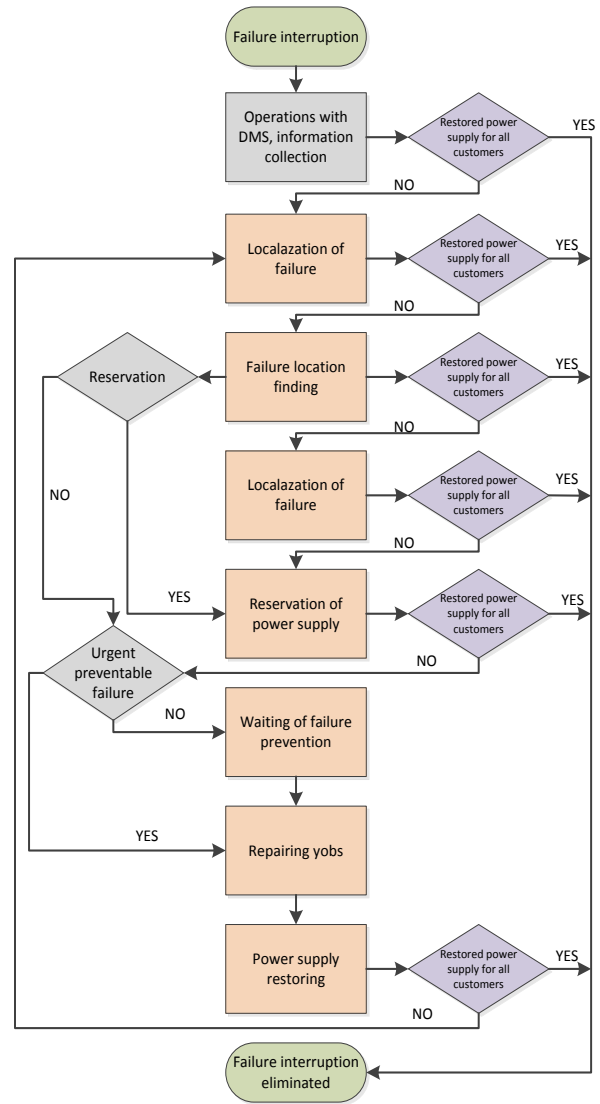


Fig. 4. Elimination sequence of interruptions

TABLE II. FAILURES FREQUENCY AND DURATION IN LATVIAN 20KV DISTRIBUTION SYSTEM

	20/04kV substations and components in substations	Overhead lines	Circuit breakers	Switches
Total interruption duration	Beta	Gamma	Exponential	Exponential
Waiting of failure prevention duration		Beta		
Failure location finding duration	Weibull	Weibull		Exponential
Failure localization duration	Weibull	Exponential	Beta	Beta
Reservation duration	Weibull	Beta	Normal	Weibull
Repairing duration	Weibull	Weibull	Exponential	Exponential
Power supply restoring duration	Weibull	Weibull	Exponential	Exponential

Interruption prevention includes operations – localizing failure, localizing and prevention of failure expansion, restoration power supply, establishing a reliable power supply, finding out the location and cause of failure, organizing

repairing works. The report includes information of interruption starting time, switching, protection operations, restoring duration (Fig.4., Table II).

In interruptions analysis total duration was divided into a maximum of 6 sections – failure location finding, localization duration, reservation, waiting of failure prevention, repairing works and power supply restoring duration. Total interruption duration may last from several minutes to 24h or more [11].

III. SOLUTION FRAMEWORK

A. Main model concept

The goal of this paper is to examine the impact of network components on distribution reliability.

The following tasks are defined to reach the goal:

- analyze the existing statistics of real network components failures;
- define probability distribution function for the duration of each restoration step;
- develop the mathematical model suitable for network reliability analysis;
- develop the computer model for a simulation of network failures in different time periods and for different network types, taking into account energy usage, load factors, length of lines, configuration of network and amount of customers;
- analyze the statistics and the suitability of the developed model for the application of optimization algorithms [9].

The specific mathematical and computer model is developed for network analysis and evaluation of the influence of the location and quantity of power switches on the network performance.

Customers are grouped by:

- private customers;
- public and government customers;
- agricultural customers;
- industrial customers;
- commercial customers.

Customer activity factor is depended on the time, when outage occurred. The equations for calculating the expected costs of customer outage (ECOST) are developed from expected energy not supplied (EENS) index. The ECOST is defined as [9]:

$$ECOST = \sum_{i=n}^m ECOST_i, \quad (1)$$

where $ECOST_i$ - expected cost of customer outage in each customer group;

n - customer group.

m - sum of customer groups.

The ECOST of outage costs can be calculated by the used man-hours, expected energy not supplied, sum of implicated customers, electrical power tariff and the salary of employed persons. In this calculation, the cost of used materials is not taken into the account.

Expected energy not supplied for one customer type can be calculated by multiplication of outage duration with annual electrical power consumption:

$$EENS_i = t_a \cdot P_v, \quad (2)$$

where $EENS_i$ - expected energy not supplied;

P_v - average annual electrical power consumption, kWh/year;

t_a - outage duration, h.

Customer outage costs are evaluating using a calculation of separate customer groups. The sum of customer outage costs can be calculated as shown below:

$$ECOST = \sum_{i=n}^m p_i \cdot ECOST_i, \quad (3)$$

where p_i - customer activity factor [2].

Expected customer outage costs can be evaluated by foregone income, turnover of customers, additional outcomes, e.g., stuff, materials, purchased electrical power, completing items, and customers' activity factor.

ECOST can be written as:

$$ECOST_i = \frac{E_i}{8760} \cdot t_a, \quad (4)$$

where

E_i - average customer annual incomes.

An often used index in reliability cost analysis is the interrupted energy assessment rate (IEAR), which is calculated as the ratio of the ECOST and the EENS at either the load buses or for the overall system, as shown below:

$$IEAR = \frac{ECOST}{EENS}. \quad (5)$$

Also different factors are taken in account:

- hour factor $f_h(t)$ setting up energy usage ratio for different hour intervals during the daytime;
- weekday factor $f_w(t)$ setting up energy usage ratio for workdays, Saturdays and Sundays;
- month factor $f_m(t)$ setting up energy usage ratio for each month during the year [12];
- amount of customers N ;
- average customers income $C(d)$ (€/year);
- outage duration t_d (h)[14, 15].

$$ECOST(t, N, d) = N * f_m(t) * f_w(t) * f_h(t) * C(d) * t_d \quad (6)$$

Three years of the work of each network type with forecasting failures were calculated and simulated.

The switch allocation problem consists of choosing which switches must be opened or closed to minimize the amount of unsupplied customers after the isolation of outage. The switch allocation problem in a radially distribution network belongs to the family of combinatorial optimization [3].

Main evaluation criteria are:

- total energy not served in KWh for customers caused by failures of network components;
- total direct costs in EUR caused by unsupplied energy to all non-private customers;
- total indirect costs in EUR for private customers;

- average outage duration [12].

Three types of network are simulated:

- urban network;
- suburban network;
- average network.

Networks differ by transformer point power, load of each transformer point, load factor, type of customers, and number of customers for each transformer point, income of each customer type depending on customers' location, power switch location and the length of the lines.

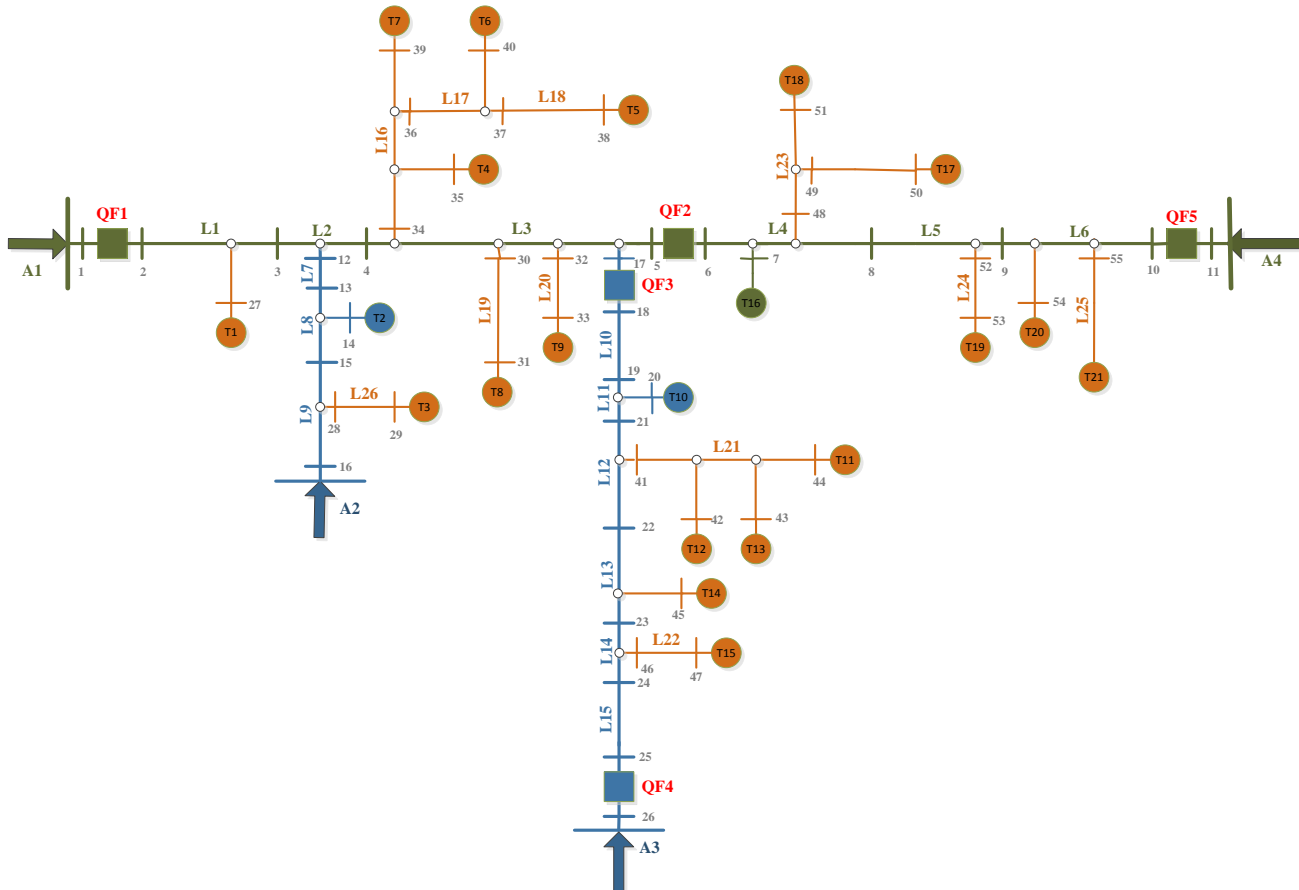


Fig. 5. Model of distribution system

Binary encoding of power switch location gives possibility to use evolutionary algorithms for the optimization of network. The developed model of the network and processing algorithms are completely suitable for multi-criteria optimization of the network.

The location of power switches are encoded as a binary string allowing to allocate them to the different sections of the network.

B. Case studies

An intelligent search algorithms as a specific modifications of the classical A-Star algorithm are developed to define the possibility of energy supply reservation from other energy source points. It provides possibility to analyze the status of each customer during the each power supply restoration sequence step after outage.

The simulated network consists of 4 energy sources, 43 switches, 45 lines, 21 transformer points and 4 power

switches, where A – energy source, L – lines, 1-42 – switches, QF- power switches, T – transformer points (Fig. 5).

The binary string of the experimental network consists of 46 variable allocation points for the power switches, and value 1 means that the power switch is allocated.

Following parameters for the genetic algorithm have been used:

- population size – 10;
- elite size – 20% of population size;
- crossover rate – 0.8;
- mutation rate – 0.02;
- selection type – random;
- crossover type – uniform using binary template.

The stopping criterion for the optimization is when the best results of the optimization were not changed during 15 generations.

The results of simulation based on genetic algorithm depending on model of network, different price of energy unsupplied, taking into an account existing and future probability distribution function for the duration of each restoration step and for different power switch allocation.

Maintenance and investment costs are taken into account in simulated networks, the number of power switches have influence on the simulation results, because the higher number of power switches, the bigger probability of failure. Therefore, the genetic algorithm intends to reduce the number of power switches keeping the minimal value of the fitness function.

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The model can be used based on analytical calculation, on Monte Carlo simulation and on genetic algorithm. For evaluation of performance of the proposed methodology there are compared different types of switch allocations in the network.

For calculation of the total costs of outage for different type of network and different switch allocations following cases can be defined:

- **Case 1:** analytical average IEAR (€/kWh) calculation for private, public and government, agricultural, industrial and commercial customers for urban, suburban and average network types;
- **Case 2:** simulation based on Monte Carlo simulation with distribution system model for all types of customers and for urban, suburban and average network types;
- **Case 3:** simulation based on Monte Carlo simulation for distribution system model with one additional power switch (in three different locations) for all types of customers and for urban, suburban and average network types;
- **Case 4:** simulation based on Monte Carlo simulation for distribution system model with two additional power switches (in different locations) for all types of customers and for urban, suburban and average network types;
- **Case 5:** simulation based on Monte Carlo simulation for distribution system model with three additional power switches for all types of customers and for urban, suburban and average network types;
- **Case 6:** simulation based on genetic algorithm for distribution system model for all types of customers and for urban, suburban and average network types.

C. Results of realibility evaluation

Results of **Case 1** of analytical calculation of IEAR for private, public and government, agricultural, industrial and commercial customers for urban, suburban and average are shown in Fig.6-Fig.8 and Table III [13].

TABLE III. COMPARISON OF IEAR (€/kWh)

Customer type	Finland	Norway	The Netherlands	USA	Sweden	Latvia	Average in Latvia
Private customers	2 -7	0,98	16,4	7 - 10	2-5	0.77-5.22	2.22
Agricultural customers	3 - 13	1,83	3,9	15	3-10	0.68-7.58	3.53
Commercial customers	2 - 47	12,07	7,9	60	5-124	1.82-25.92	12.67
Public and government customers	5 - 41	1,59	33,5	80	3-30	0.31-19.07	6.85
Industrial customers	4 - 20	1,59 - 8,05	0,3 - 33,1	17 - 56	10-47	0.89-19.63	6.85

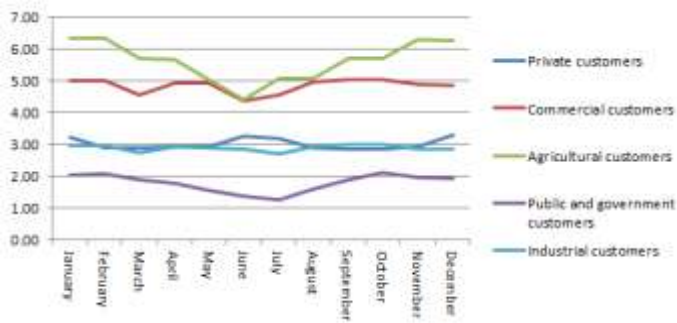


Fig. 6. IEAR [€/kWh] for average distribution network type

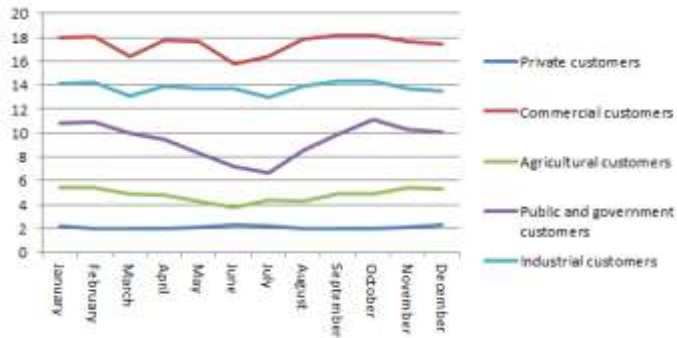


Fig. 7. IEAR [€/kWh] for suburban distribution network type

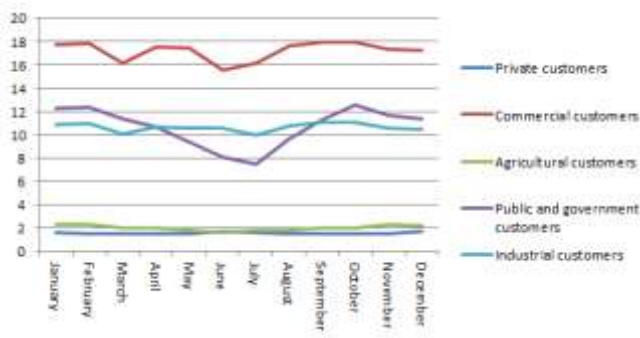


Fig. 8. IEAR [€/kWh] for urban distribution network type

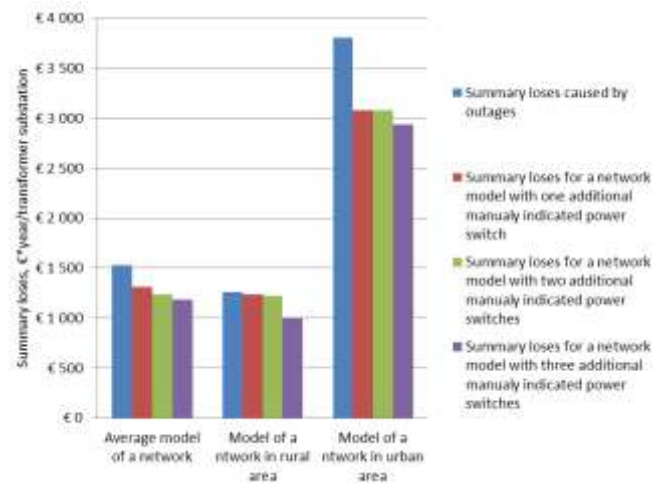


Fig. 9. The summary losses resulting from outages

In order to improve security of electricity supply, thereby reducing the losses resulting from failure of power supply, the optimal placement of power switches in network plays an important role. If there is no optimal element placement in the network, it can lead to a situation that the accumulated losses from the power failures will increase and / or reduce insignificantly, as well as it is impossible to calculate the utility of capital investments for improving of the effectiveness of the reliability level by manually specified locations of elements [9].

In the **Case 6**, the genetic algorithm has been used for the calculation of the optimal allocation of power switches. Resulting from failures by additionally installed power switches and their placement in network main lines and bond lines taking into account costs of investments and failure prevention, provides an opportunity to choose optimal power switch number and placement in the network, thus minimizing the losses for distribution network, society and losses for users caused by failure, as well as minimizing power unsupplied duration. The count and placement optimization of power switches was carried out according to principles used in previous algorithms and using investment and failure prevention costs criteria in multi-criteria analysis additionally. The number and placement optimization of power switches was carried out taking into account the failure prevention and investment costs for an average distribution network model, a distribution network model in rural area and a distribution network model in urban area, with loan periods - 10 years, 25 years and without loan. For an average model of power supply network with minimized duration of summary failures of power supply and minimized losses to the distribution network, public and users resulting from failures of electrical power, the optimum power switches number for 10 and 25 years loan period and without loan is 2 units. For a distribution network model c with minimized duration of summary failure of power supply and minimized losses to the distribution network, public and users resulting from failures of electrical power, the optimum power switches number for 25 years loan period and without loan is 2 units, but for the 10 year loan period is 3 units (Fig 10.). For a distribution network model in rural area with minimized duration of summary failure of power supply and minimized losses to the distribution network, public and users resulting from failure of electrical power, the optimum power switches number for 10 years loan

The results of simulation based on Monte Carlo simulation for **Cases 2-5** are shown in Fig 9. This calculation is made in order to estimate the losses and reliability indices of a chosen network model. Monte Carlo method-based calculation of the reliability and losses estimation allows obtaining more accurate information by using probability distributions, thereby obtaining more accurate information. The advantage of the method is the speed of calculation and diversity of the data acquired.

period and without loan is 2 units, but for the 25 year loan period is 3 units. At minimized total duration of power failures and minimized losses caused by power failures to distribution network, society and users, the minimum number of power switches at an optimal placement for 10, 25-year loan periods and without loans has shown at Fig. 2. It can be concluded, that the total benefits resulting from optimal number and location of power switches are identical to the total investment costs (Fig. 10).

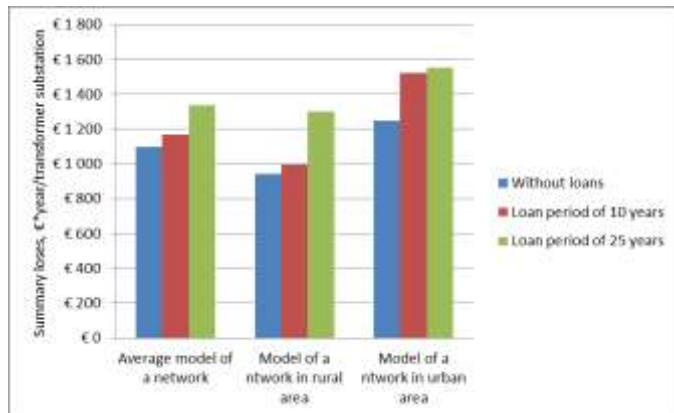


Fig. 10. Results of the optimization of a number and placement of power switches

Conclusions

The optimal allocation of power switches can achieve reductions in costs and outage durations.

This paper proposes a solution based on analytical calculation, Monte Carlo simulation and genetic algorithm simulation. The case studies use real network configuration and real network data. The results demonstrate that the methodology can be used for optimal switch allocation and for optimal customers' outage costs estimation using real customers' incomes data. The investment cost is deterministic in nature and can be obtained using well-established methods. The customer outage cost is a function of outage frequency, duration, load lost, location, and societal effects.

In the paper can be seen that number of power switches and their location are important, but too high quantity of power switches and/or incorrect location of them may increase not supplied energy volume and customers' direct costs. Therefore the optimization of location of power switches is necessary. The offered method of power switches allocations can help distribution system operators in their decision making process regarding to amount and allocations of power switches. Optimal power switch allocations can help in the investment decision process for distribution system operators.

Effective allocation of power switches improves SAIDI and can improve reliability of distribution system.

For optimal power switch allocations and for economical point of view the next step is to evaluate power switches allocations depending on maintenance costs and investment costs.

The paper illustrates the calculation of the ECOST (expected costs of customer outage) and the related IEAR (interrupted energy assessment rate) indices in Latvian distribution network.

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