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# RELIABILITY ANALYSIS OF MEDIUM VOLTAGE FEEDER

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# Abstract

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Reliability analysis of medium voltage feeder
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Distribution companies are facing numerous challenges in the near future. Regulation defines correlation between power quality and revenue cap. Companies have to take measures for reliability increase to successfully compete in modern conditions.

Most of the failures seen by customers originate in medium voltage networks. Implementation of network automation is the very effective measure to reduce duration and number of outages, and consequently, outage costs. Topic of this diploma work is study of automation investments effect on outage costs and other reliability indices. Calculation model have been made to perform needed reliability calculations. Theoretical study of different automation scenarios has been done. Case feeder from actual distribution company has been studied and various renovation plans have been suggested.

Network automation proved to be effective measure for increasing medium voltage network reliability.

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**Abbreviations and symbols**

| | |
|---|---|
| ASAI | Average service availability index |
| BU | Backup |
| CAIDI | Customer average interruption duration index |
| CAIFI | Customer average interruption frequency index |
| CENS | Compensation for Energy Not Supplied |
| DMS | Distribution Management System |
| DR | Delayed Reclosing |
| EMA | Energy Market Authority |
| HSR | High-Speed Reclosing |
| LV | Low Voltage |
| MAIFI | Momentary average interruption frequency index |
| MCD | Manual Controlled Disconnector |
| MV | Medium Voltage |
| NIS | Network Information System |
| PQ | Power Quality |
| RCD | Remote Controlled Disconnector |
| RITM | Repair and isolation time matrix |
| SAIDI | System average interruption duration index |
| SAIFI | System average interruption frequency index |
| SCADA | Supervisory Control and Data Acquisition |
| VAT | Volume Added Tax |
| WTA | Willingness To Accept |
| WTP | Willingness To Pay |

| | |
|---|---|
| $a$ | annuity |
| $C$ | cost |
| $f$ | frequency |
| $L$ | length |
| $P$ | power |
| $T$ | time |

Subindexes

| | |
|---|---|
| ADD | additional |
| BU | backup |
| MC | manual-controlled |
| PF | permanent fault |
| R | repair |
| RC | remote-controlled |
| T | total |

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# 1 Introduction

In the past, the distribution system received less attention than have generation and transmission segments, when speaking about system reliability and therefore the distribution segment has been the weakest link between the supply of energy and the customer, who utilised the energy. This is due to the fact that generation and transmission segments are very capital intensive, and outages in these segments can have widespread catastrophic economic consequences to both utilities and customers.

System reliability is an important factor in modern distribution environment. It affects directly the revenue of utilities and their position in competitive environment.

Reliability improvements along with cost reduction are among the most complex problems faced by electricity distribution companies nowadays. For successful performance in modern conditions application of modern technologies is essential. The topic of the diploma work is feeder reliability study and study of one of the approaches to reliability improvement, which help to reduce and optimize expenses.

Chapter two gives overview of distribution network, challenges, met by distribution companies and describes switching equipment.

Chapter three explains reliability calculations, reliability indices and the role of reliability in network planning process.

Chapter four describes reliability model which has been developed. Using that model, theoretical analysis has been performed.

Case study of rural distribution feeder is presented in chapter five.

# 2 Electricity distribution networks and reliability

As a result of historical development and due to technical limitations and economic feasibility, electricity is generated centrally at power stations. Placement of the stations is often determined by proximity of natural resources (such as coal and water) and customers are situated far from the stations and distributed in space. Electricity is transmitted to the customers through transmission networks of high voltage and then through distribution networks, which are the subject of this study. Figure 1 illustrates the process of generation, transmission and distribution of electric energy.

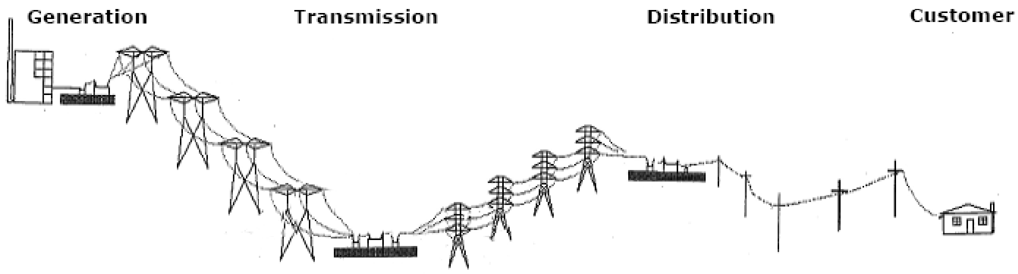



Figure 1. Transmission and distribution of electric energy

This chapter describes distribution system, its importance for reliability of supply, problems of modern distribution networks and types of switching equipment, which have direct effect on reliability.

## 2.1 Description of distribution networks and network structures

Distribution network is a complex of substations, switching centres and power lines designed to transmit electrical energy from the transmission network to the end-customer. Distribution costs make significant part of electricity price, especially for smaller customers. As Figure 2 shows, distribution costs account for 31 % of the electricity price for domestic customers in Finland.

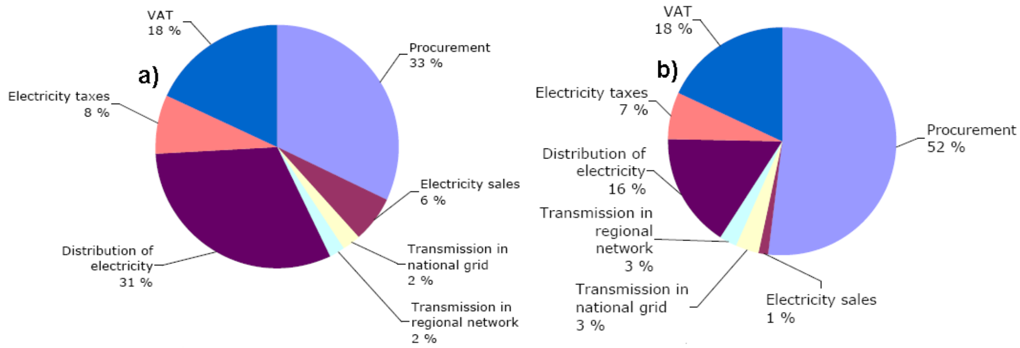



Figure 2. Components of electricity price for a) domestic customer; b) medium-scale industrial customer in Finland (EMA 2007)

Also, distribution network are the place, from which most of interruptions seen by customers origin (Lakervi, Partanen 2008). Transmission network is built in such way, that interruptions which happen in it are usually not seen by customers, and interruptions in low-voltage network most often affect only small number of customers. When fault happens in the medium voltage feeder, usually all customers connected to this feeder suffer from electricity outage for some period of time. One of the topics of this work is how to decrease this outage time.

Distribution network characteristics strongly influence voltage quality, because voltage on the medium voltage (MV) busbars of primary substations can be considered constant, and there are no on-load voltage regulating devices in low-voltage (LV) network. In Finland distribution networks include regional network (110 kV and 45 kV), medium-voltage network (20 kV) and low-voltage network (0.4 kV).

### *2.1.1 Medium-voltage networks*

Medium voltage network is the link between regional networks and low-voltage networks. In Finland voltage typical of the MV networks is 20 kV, 10 kV is used in some old city networks. Most often, medium voltage lines are built in radial topology, but also some parts of the network are constructed in mesh topology. MV lines are connected to primary 110/20 kV substations with circuit breakers equipped with number of relay protection schemes. MV networks consist both of overhead lines and underground cables. In rural areas overhead lines prevail, there are only few back-up connections, lines can have big lengths and low transmitted power. In the cities underground cable networks are widely used. High concentration of the load with high reliability requirements on relatively small territory is the cause of network design with more backup connections and loops – mesh topology. In Finland in MV networks neutral point is either isolated or earthed through arc-suppression coil.

### *2.1.2 Low-voltage networks*

LV network is the last part of the distribution system before consumer. In Finland three-phase 0.4 kV networks are used. Electricity is transformed to low voltage at the 20/0.4 kV distribution substations, which are constructed in different ways depending on placement and rated power. In rural areas, where powers are low and environmental requirements are not so strict, distribution substations are often pole-mounted with connection to MV feeder through disconnector. In city areas distribution substations are more often kiosk-type or placed in basement or underground, MV feeder can be connected using circuit breaker. LV lines are usually radially operated. Lengths of lines and power transmitted through them are varied in very wide range depending of special density of the load. LV networks use earthed neutral. Because of proximity to population, LV networks should have reliable protection.

## 2.2 Description of challenges in distribution networks

There are several challenges and incentives to large network infrastructure renovation. Next, the most important factors are presented.

### *2.2.1 Load growth*

Because of constantly increasing application of electricity in modern life, overall electricity consumption is growing. But this process does not flow similarly on all territories, there are areas of fast extensive development, areas, where electricity consumption have stabilized and even areas with declining demand for electricity. Load is concentrated mostly in population centres, but also tendency of load growth in countryside is observed because of popularity of holiday homes.

Load growth may lead to more frequent equipment overloads resulting in higher fault levels especially in distribution transformers. Load growth can also appear as higher voltage drops and weaker voltage quality. Increasing load leads to higher outage costs if reliability development demands have not been taken into account.

### *2.2.2 Power quality demands*

In the past, customers were much less sensitive to the outages, especially momentary. As a result of wide use of loads sensitive to short interruptions, such as computers, microwave ovens, other consumer electronics and wide application of electricity in vital processes, higher level of reliability is required. Growing contribution of such load types as consumer electronics, electrical drives and different power converters leads to decrease in voltage quality. At the same time, customer expectations for power quality level are steadily increasing. Compensation for Energy Not Supplied (CENS) values have been increasing during last years and this tendency is still actual (Kumpulainen et al. 2007). Power quality benchmarks become deeper integrated into the regulation of distribution business: power quality will determine the revenue cap for utilities. Regulation makes companies to increase reliability level and operate in cost-effective manner. For making this regulatory control possible, detailed outage statistics is needed. Modern metering systems should allow gathering such information. This issue is studied in more detail in chapter 3.3.

Higher reliability level means the need for investments which obviously will lead to higher electricity distribution tariffs. But not all customers are ready to pay more for the reliability. Because of that, customers have to be differentiated and places where renovation is most needed have to be determined.

### *2.2.3 Ageing infrastructure*

Significant part of the primary network equipment (lines, transformers, etc) has been built 25-30 years ago and now its lifetime is practically over. Networks that have been designed in the middle of previous century do not fulfil modern reliability requirements. Ageing of infrastructure leads to higher level of faults and higher outage costs. Loads increased significantly since the construction time of the equipment, and it needs to be renovated at least to correspond to present day loads. Replacement of all old infrastructure seems to be economically unjustified, and the most effective methods of renovation have to be determined.

### *2.2.4 Climatic changes and environmental requirements*

There are different versions about the cause of the global warming and if it is really global change of climate, caused by human activity or something else, or just one of the natural variations in the historical timescale. But at the present day, it can be said that the trend of global temperature increase is still actual, and power industry have to deal with its consequences.

Direct effect of the temperature rise for distribution networks is the increase of active resistance which leads to greater amount of the active power losses. More losses, for example, in transformers means that more energy should be spent on their cooling and their peak load capability becomes lower if no measures applied. More problems bring the growing active usage of cooling systems during hot weather which leads to significant increase of load. Hence, peak load is observed during the time which is the most difficult for the network equipment from the thermal conditions point of view. On the other side, loads are lower in winter, during the other time of peak consumption.

The other result of global climatic changes is increase in windiness and thunderstorm frequencies, which leads to higher fault probabilities. Fault rates related to bad weather conditions can be increased by 50 % compared to present (Kumpulainen et al. 2007).

Environmental organizations are going to prohibit effective impregnations, which are used for wooden poles. This will require the use of alternative impregnations, which provide shorter lifetime, or use of concrete or metal poles. All these measures will result in higher construction costs for overhead lines.

Increase in atmospheric precipitation results in number of negative effects for the distribution networks. More frequent rains soften the soil, which means more difficulties in construction works. Trees fall near the lines as a result of softening of the soil or increased snow load in winter. Floods and increase in ground waters level are dangerous for underground cabling and substations.

All these environmental challenges increase the need for paying attention to network reliability.

## 2.3 Description of network switching equipment

Switchgear is group of devices intended for opening or closing electric circuit. The main functions of switchgear are *protection* against overload and short-circuit currents and insulation failures, *isolation* of the part of the system and *control* such as operational and emergency switching and switching for maintenance.

The types of switchgear discussed in this work are disconnectors, circuit breakers and reclosers.

### *2.3.1 Disconnectors*

Disconnector is a device for opening or closing the de-energized circuit. When open, it should create a clearly visible gap. It is not designed to disconnect operational or short-circuit current, but should withstand short-circuit current running through it.

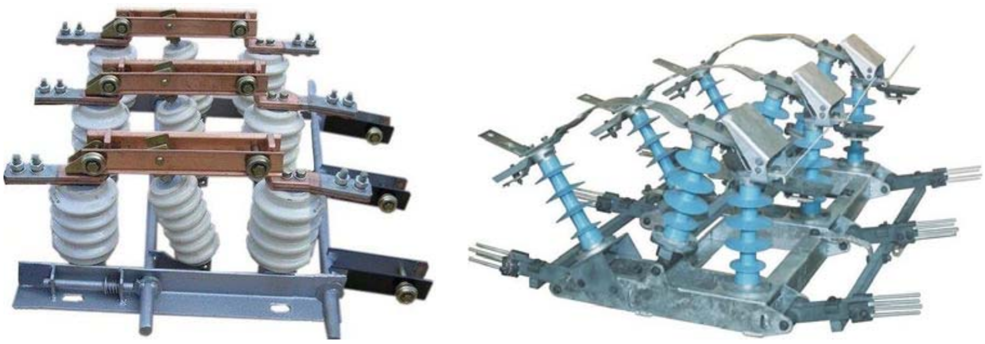


Figure 3. Medium voltage disconnectors

Disconnectors can be either manual-operated using control handle or remote-controlled. Remote-controlled disconnector except disconnector unit itself includes control drive, control electronics and radio-communication unit.

Figure 4. Remote-controlled disconnector.

Remote-controlled disconnectors significantly reduce time, needed to isolate faulted part of the circuit, and, thus, significantly reduce outage time for the non-faulted upstream part of the feeder. With remote control, disconnection time is practically equal to time needed to determine the location of fault. Remote-controlled disconnectors are usually used at important nodes of the feeder and at the backup connection points.

### *2.3.2 Circuit breakers*

Circuit breaker is a type of switchgear that is able to switch off fault currents. Their construction incorporates special chambers for quenching of the electric arc. There are several types of circuit breakers, divided by the method of arc quenching: oil, gas, vacuum, air.

Figure 5. Vacuum 20 kV circuit breaker (left), oil 10 kV circuit breaker (right)

Circuit breakers are used on the primary substations and automatically controlled by relay protection for immediate operation in case of fault.

### 2.3.3 *Reclosers*

Recloser is a pole-mounted or pad-mounted circuit breaker equipped with voltage and current transformers, microprocessor relay protection and automation, autonomic power supply and communication equipment. Reclosers are used to protect customers from the faults at the downstream part of the feeder. Reclosers reduce frequency and duration of faults seen by customers.

1) 2) 3)

Figure 6. 1) pole-mounted recloser; 2) control cabinet; 3) switching module

Recloser can operate with or without communication with distribution system control centre. Several reclosers can be coordinated used different protection settings or through communication channels. Recloser is a key component for building decentralised network automation. Operation principle of decentralized distribution network is shown in the Figure 7. When a fault happens, automation should work in order to isolate only the faulted part of the system without interrupting customers in non-faulted areas.

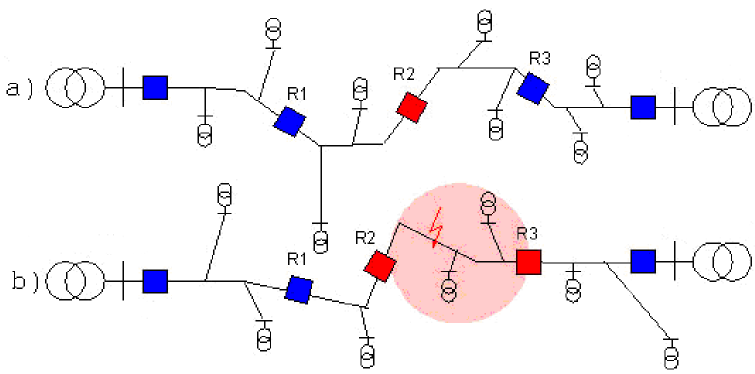



Figure 7. Decentralized automation of distribution feeder a) network state before the fault, b) network state after the fault, R1, R2, R3 – reclosers, area de-energized after the fault is shown in red circle (Vorotnitsky)

Figure 7 shows feeder with two supply sources. Recloser R2 is normally open. When fault happens on section between reclosers R2 and R3, the latter opens, isolating the fault. Thus, customers outside the faulted area do not see this interruption. If fault would happen, for example, between R3 and substation, switchgear on the substation and R3 would open, isolating the fault and R2 would close, making it possible for customers between R2 and R3 to get supply from other substation.

In the USA 4-wire distribution networks with dead-earthed neutral are used. (Titenkov) Network design conception is to minimize length of low-voltage lines. Each customer is supplied using its own single-phase MV/LV transformer, connected to phase voltage. Branch lines are protected with fuses. Feeder sections are separated by reclosers. Feeder taps are protected using sectionalizers (switchgear which is designed to automatically open the de-energized circuit).

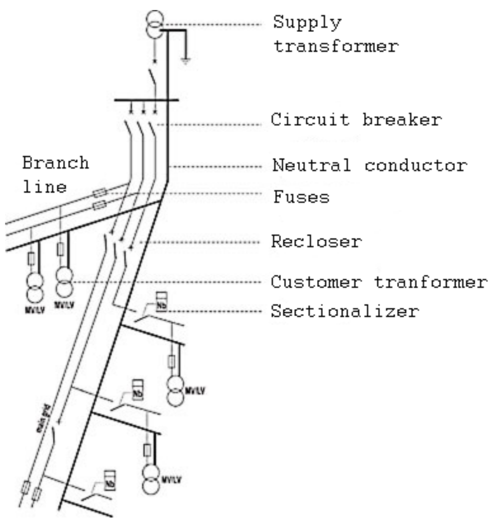



Figure 8. 13.8 kV network in the USA (Titenkov)

This network topology makes use of single-phase reclosers or three-phase reclosers with single-phase trip/triple-phase lockout and single-phase trip/single-phase lockout operation modes. Studies have shown that approximately 80 % of distribution system faults are single-line-to-ground (Taylor 2008). Many faults on overhead systems are temporary. Single-phase tripping and lockout can reduce the number of momentary interruptions, number of sustained interruptions, and interruption duration, therefore reducing MAIFI, SAIFI, and SAIDI. Figure 9 shows scheme operation during 1-phase fault.

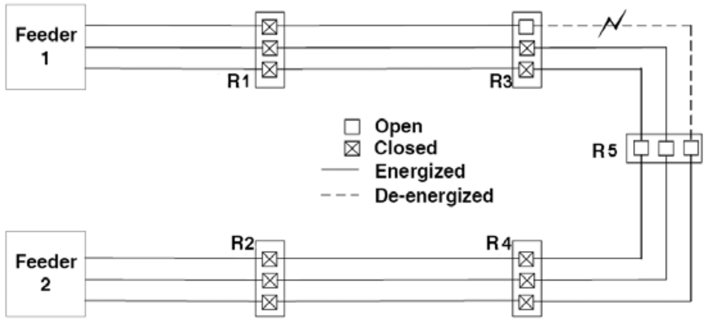



Figure 9. 5-recloser loop scheme (Taylor et al. 2008)

Recloser R5 is normally open. Reclosers R3 operates in single-phase trip/single phase lockout mode. When fault happens on one phase of the feeder, R3 disconnects faulted phase, and customers, which are connected to other phases of faulted section, do not experience the interruption.

# 3 Basics of reliability calculations on medium voltage feeder

This part gives theoretical basis for calculation of reliability characterizing indices, commonly used to assess performance of the distribution system. Ways of definition of unit outage costs are described. Also, different techniques for calculating outage costs are explained. Paragraph about role of outage costs in the system planning ends this chapter.

## 3.1 IEEE electric power distribution reliability indices

These indices were introduced to uniform data about power system reliability, to identify factors which affect the reliability level, to provide useful tool for comparison of utilities performance. The indices are intended to apply to distribution systems, substations, circuits, and defined regions. The indices are commonly used all over the world. Definitions of indices are from IEEE Guide for Electric Power Distribution Reliability Indices.

### *3.1.1 System average interruption frequency index (SAIFI)*

The system average interruption frequency index indicates how often the average customer experiences a sustained interruption over a predefined period of time. Mathematically, this is given in Equation (1).

$$\text{SAIFI} = \frac{\Sigma \text{ Total Number of Customers Interrupted}}{\text{Total Number of Customers Served}} \tag{1}$$

### *3.1.2 System average interruption duration index (SAIDI)*

This index indicates the total duration of interruption for the average customer during a predefined period of time. It is commonly measured in customer mutes or customer hours of interruption. Mathematically, this is given in Equation (2).

$$\text{SAIDI} = \frac{\Sigma \text{ Customer Interruption Durations}}{\text{Total Number of Customers Served}} \tag{2}$$

### *3.1.3 Customer average interruption duration index (CAIDI)*

CAIDI represents the average time required to restore service. Mathematically, this is given in Equation (3).

$$\text{CAIDI} = \frac{\Sigma \text{ Customer Interruption Duration}}{\text{Total Number of Customers Interrupted}} \quad (3)$$

### *3.1.4 Customer average interruption frequency index (CAIFI)*

This index gives the average frequency of sustained interruptions for those customers experiencing sustained interruptions. The customer is counted once regardless of the number of times interrupted for this calculation. Mathematically, this is given in Equation (4).

$$\text{CAIFI} = \frac{\Sigma \text{ Total Number of Customers Interrupted}}{\text{Total Number of Customers Interrupted}} \quad (4)$$

### *3.1.5 Momentary average interruption frequency index (MAIFI)*

This index indicates the average frequency of momentary interruptions. Mathematically, this is given in Equation (5).

$$\text{MAIFI} = \frac{\Sigma \text{ Total Number of Customer Momentary Interruptions}}{\text{Total Number of Customers Served}} \quad (5)$$

### *3.1.6 Average service availability index (ASAI)*

The average service availability index represents the fraction of time (often in percentage) that a customer has received power during the defined reporting period. Mathematically, this is given in Equation (6).

$$\text{ASAI} = \frac{\text{Customer Hours Service Availability}}{\text{Customer Hours Service Demands}} \quad (6)$$

Also, number of other indices exists. Distribution system performance can be evaluated through the use of reliability indices. To adequately measure performance, both duration and frequency of customer interruptions must be examined at various system levels. The most commonly used indices are SAIFI, SAIDI, CAIDI and ASAI (Warren at al. 1999). All of these indices provide information about average system performance. Many utilities also calculate indices on a feeder basis to provide more detailed information for decision making. In order to describe the feeder reliability performance, FAIFI (Feeder Average Interruption Frequency Index) and FAIDI (Feeder Average Interruption Duration Index) are defined by replacing *system* in title definition of SAIFI and SAIDI by *feeder*. FAIFI and FAIDI indicate that each customer on the feeder will expect to encounter how many interruptions and how many minutes per year in average respectively. (Billinton 1995)

Days, when large outages (more than 10 % of load) occur are called major event days. These events should be handled separately from usual day-to-day statistics, because major event day performance often distorts and masks daily performance. Not performing this critical step can lead to false decision making. Also, interruptions that occur as a result of outages on customer owned facilities or loss of supply from another utility should not be included in the index calculation (IEEE 1994).

## 3.2 Definition of outage costs

Nowadays distribution companies are in the market conditions, where regulation forces them to seek for ways for optimizing their performance due to the fact, that their profit is now regulated. The regulation of network business created also a need to measure the efficiency of network companies (Kivikko et al. 2004).

In the past the usual manner of development of distribution system lead to overdimensioning it during construction. Present day conditions require satisfaction of customer needs in the cost-effective manner.

Most of the outages experienced by electricity customers originate in the medium-voltage networks. Outage costs need to be defined for use during network planning and modelling. Measures for outage costs are €/kW and €/kWh. Cost of non-delivered energy differs significantly from energy tariffs. During supply outages customer may experience significant losses due to breaks in production cycles, spoiling of the materials, melting food in refrigerators, etc. The outage can cause both direct and indirect harm. Loss of production and raw materials, lack of comfort in the life are direct results. While other damages such as crimes due to absence of street illumination, cancellation of orders as a result of late deliveries can be indirectly caused. Outage cost should be estimated in monetary value, which is quite difficult without direct interaction with customers. Estimating the impacts on raw materials damaged during an outage is possible whereas estimating the impacts on life is somehow not easy, for example. This is so because each customer has own requirements to power quality and purpose of electricity usage. Consumer categories, power quantity not supplied, interrupted activities, duration and period of outages should thus be the criteria of cost estimation (ERI 2001). As a result, outage costs are notably higher than price of purchased electricity (Lakervi, Partanen 2008), and differ for various customer groups. To define outage costs, statistical data for different times of outage, for different customer groups is needed. Such data is not always readily available, and for example in Finland, last time it was collected during regulation period 2005-2008. In this connection customers were divided into five groups: residential, agricultural, industry, public and commercial. The outages were divided into four categories: long fault interruptions, planned maintenance outages and short auto-reclosings (i.e. < 1 second and < 3 minute). Reliability calculation tool was used to study the structure of total interruption costs (i.e. what percentage of interruption costs is caused by certain customer group and certain interruption type). Usually major part (even over 80 %) of customers' interruption times is caused by outages in medium voltage networks and thus only these outages were considered. (Kivikko et al. 2004)

The main values that were defined during that study were the WTP – Willingness To Pay for avoiding the outages, and WTA – Willingness To Accept – amount of money which customer wants to get for accepting the 1 hour outages (which is much greater than WTP). Customers filled the questionnaires about their requirements to quality of supply. Obtained discrete values were linearly interpolated and after that values for planned and unexpected outages were derived by multiplying the values for 1 hour outages with some coefficients. As further analysis revealed, costs of high-speed reclosings and delayed auto-reclosings make a significant part of total outage costs – and it's desirable to find the ways to reduce the number of short outages. Results of these studies are shown in Table 1.

Table 1. Unit costs for power quality factors for customer groups in Finland (Lakervi, Partanen 2008)

| Customer | Permanent faults | | Planned interruptions | | Auto-reclosings | |
|---|---|---|---|---|---|---|
| | | | | | High-speed | Delayed |
| | €/kW | €/kWh | €/kW | €/kWh | €/kW | €/kW |
| Residental | 0.36 | 4.29 | 0.19 | 2.21 | 0.11 | 0.48 |
| Agriculture | 0.45 | 9.38 | 0.23 | 4.8 | 0.2 | 0.62 |
| Industry | 3.52 | 24.45 | 1.38 | 11.47 | 2.19 | 2.87 |
| Public | 1.89 | 15.08 | 1.33 | 7.35 | 1.49 | 2.34 |
| Service | 2.65 | 29.89 | 0.22 | 22.82 | 1.31 | 2.44 |

Table shows unit outage costs for different customer groups. To find outage costs parameters for certain part of the network, these parameters have to be multiplied with customer structure percentage and summed up in the columns.

Outage costs are calculated separately for different types of interruptions, because fault and maintenance frequencies are varied and restoration times are dependent on topology of feeder and interruption time. Figure 10 illustrates the process of outage costs calculation.

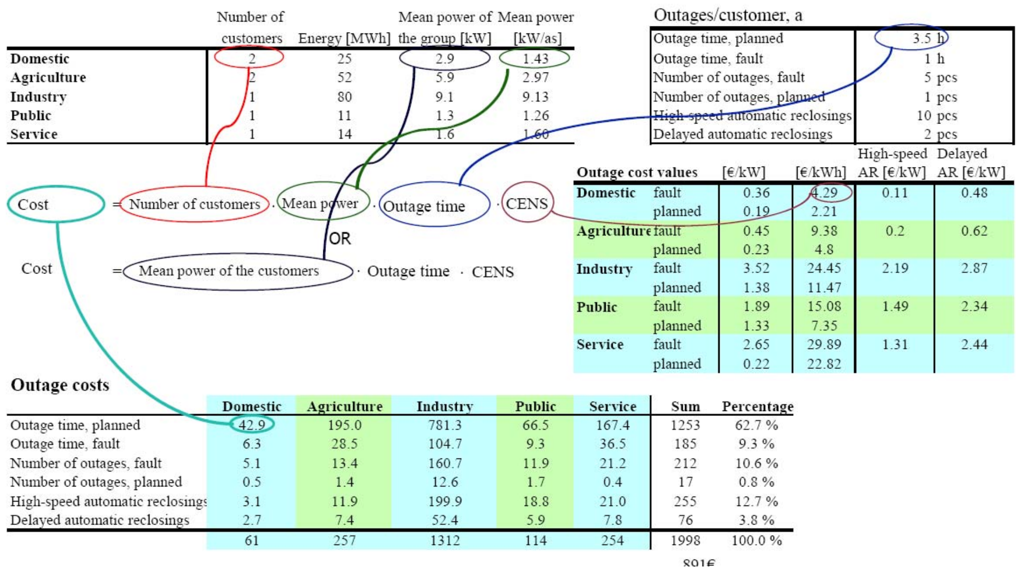



Figure 10. Calculation of outage costs (Lakervi, Partanen 2008).

Thus, factors affecting outage costs are: outage costs parameters, consumed power and outage time. To reduce outage costs, number of customers that suffer from the outage or duration of the outage should be reduced.

### 3.3 Outage costs in the long-term (strategic) planning

Generally, there is no obligation in choosing reliability levels in power system planning and operation. It mostly depends on the work experience. The task of the distribution company is to provide and supply reliable electricity to customers at reasonable prices. The prices of electricity normally depend on the reliability level that customers need or utility is able to provide, the more reliable - the higher the price. When network equipment is used close to it maximum capacity it means lower costs and lower reliability. Low reliability level leads to higher customer losses due to outages. Creating reserve of capacity and reliability requires higher expenses. The balance between economical and technical considerations is therefore necessary for utility's operation regardless of working under competitive environment or not.

One of the problems encountered by distribution companies is how to determine optimal reliability level. However, such the level can be found theoretically by comparing the cost of investments and operational costs with customers' benefits at different reliability levels. The optimum reliability level will be at the point where investments and operational costs become larger then outage costs benefit. Figure 11 illustrates finding the optimum level of reliability.

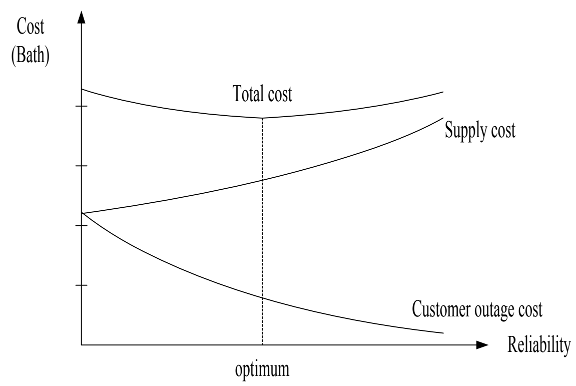



Figure 11. Costs and reliability (ERI 2001)

One of the factors that influence reliability level nowadays is regulation of distribution business. In Finland, revenue cap for distribution companies is adjusted according to several parameters, one of which is the summary outage time. Thus, increase of power quality becomes beneficial for network operators. Figure 12 illustrates regulatory effect of power quality.

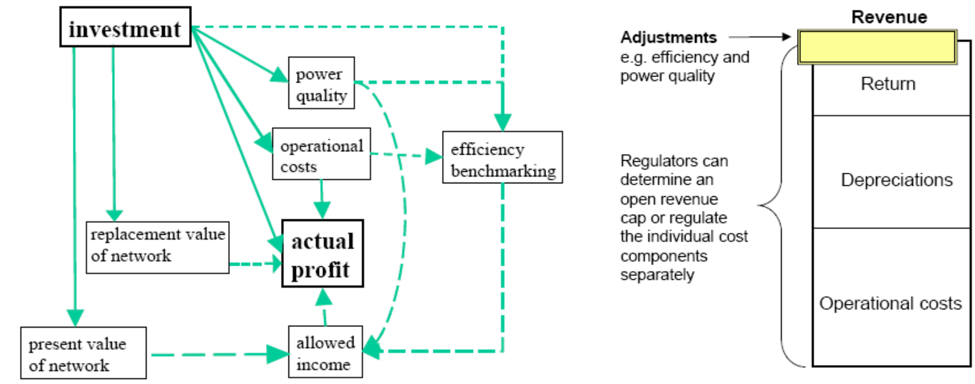



Figure 12. Left: the impacts of investments on the actual profit of a company. Effects of regulation are indicated with dashed lines (Honkapuro et al. 2005). Right: regulation adjusts revenue cap depending on power quality (Viljainen 2008).

Calculations have shown that the directing effects of the regulation model would be much better if the outages were modelled as outage costs and added to operational costs instead of only considering the summed customer outage time as a separate input parameter for the regulatory model, as it is done now (Kivikko et al. 2004).

For network planners understanding actual meaning of outage costs to the company is not matter-of-course. Complexity of distribution system where outages are observed makes it difficult to get general understanding of situation. There are different methods for evaluating power quality in distribution business, and companies themselves often meet problems in understanding the differences. From authority perspective there are several alternatives to apply outage cost into distribution business. The main outage cost methods and directing effects to network developing are presented in Table 2.

Table 2. Outage cost methods and Customer group information (Lassila et al. 2005)

| Outage cost method | Directing effects to network operation and planning |
|---|---|
| Nationwide/Company-specific<br>- no energy-weighting | All customers are equal in sense of outage costs. Consumption and customer group are neglected. (E.g. hospital vs. household) → No reasonable signal for network planning |
| Nationwide/Company-specific<br>- energy-weighting | Priority in big customers. Customer group is still neglected. (E.g. small industry vs. farm) → Big customers are in priority e.g. in fault clearance |
| Distribution substation-specific<br>- energy-weighting<br>- customer group-specific | Consumption and customer group are noticed. → Investments and network operating focus economically right places |

Outage cost method has to be chosen according to the task. Use of wrong method can lead to non-optimal selection of a place for investment. For instance, use of nationwide and non-energy-weighted method may direct investment to place where only number of customers is noticed and energy consumptions and types of customers is totally neglected. (Lassila et al. 2005)

Investments that affect power quality are rather expensive. Before planning of network renovation and comparison of these investments, it would be useful to know their possible effects. Table 3 shows impact of different investments on power quality. This work focuses mainly on network automation methods.

Table 3. Network investments and operations and their impact on PQ. (++ = strong impact, + = medium impact, - = slight or no impact) (Lassila et al. 2005)

| | Long interruptions | | Short |
|---|---|---|---|
| | Number | Duration | interruptions |
| Topology (structure) of the network | | | |
| - new primary substations | ++ | + | + |
| - new medium voltage lines | + | + | + |
| → to short [line length / switch] | | | |
| - reserve lines (meshed networks) | + | ++ | - |
| Components criteria | | | |
| - underground vs. overhead lines | ++ | - | ++ |
| - coated cables vs. overhead lines | ++ | - | ++ |
| - surge arresters | - | - | ++ |
| - earth fault current compensation | + | - | ++ |
| - forestry work on line paths | + | - | ++ |
| Network automation | | | |
| - remote-controlled disconnectors | - | ++ | - |
| - fault location system | - | ++ | - |
| → aiming forestry work | - | - | + |
| - relay settings | + | + | + |
| Organization training | | | |
| - readiness for wide interruptions | + | ++ | + |
| - network building and maintenance | | | |
| under operation (voltage work) | ++ | ++ | - |

Distribution regulation brings new requirements and challenges for interruption statistics and outage cost methods. Because of existing correlation between allowed net revenue and power quality, interruption statistics should be accurate. Methods for evaluating actual outage costs should be improved. Only companies that use most cost-effective solutions can successfully operate in the modern competitive environment. Outage costs have to be calculated at least on distribution substation-specific level so that power consumption and customer group structure would be taken into account.

# 4 Reliability model

Nowadays, practically every utility in power industry has special softwares, which help to perform necessary calculations, and distribution business is not an exception. Evolution of software for distribution companies have lead to creation of Distribution Management Systems (DMS), which are integrated solutions for automation of distribution company operations: planning, operation, maintenance, analysis, reporting, etc. Reliability calculation tools are most often implemented in DMS as a part of advanced asset management. Input data for analysis is stored in DMS databases: network configuration in Network Information System (NIS), fault frequency statistics can be obtained from SCADA (Pylvanainen et al. 2004). Calculation results are used in planning and network development processes. These tools have graphical interface and various forms of results representation.

But not all companies have DMS implemented (especially, smaller ones). The other problem is great number of input parameters, and each of them affects the result, and distribution company personnel does not always have clear understanding about their influence and how to set them properly. The method of calculations is unclear to user. There is no common knowledge for analysis of reliability information and reasonableness of power quality investments. In many cases, management systems do not provide enough information for more detailed reliability analysis. Also, sometimes, use of complicated software system is excessive and not necessary for solving number of small problems, such as optimization of single feeder or outlining the most problematic part of the system. A simple reliability calculation model could help in such cases to find solution with minimal efforts and spending minimum time. Also, it can be used for education purposes (training of personnel or education of students) and theoretical analysis.

And the last, but not least incentive for creating simplified model: there are a lot of cases, when detailed outage statistics is unavailable, and this model can be used for approximate evaluative analysis.

## 4.1 Interruption types

Fault refers to a state in which a component is not capable of performing its specified operation according to a success criterion. Interruption types can be divided in long and short ones as well as planned and unplanned interruptions.

### *4.1.1 Permanent faults*

Permanent fault – sustained fault due to external cause, which is impossible to remove by reclosings and which needs to be located and cleared. Permanent faults are less frequent than other types of faults, but cause the most outage costs because of amount of time needed to remove them. In the Figure 13 is presented permanent fault statistics from Finnish distribution companies. Average fault frequency is nowadays between 5-10 faults/100km,a.

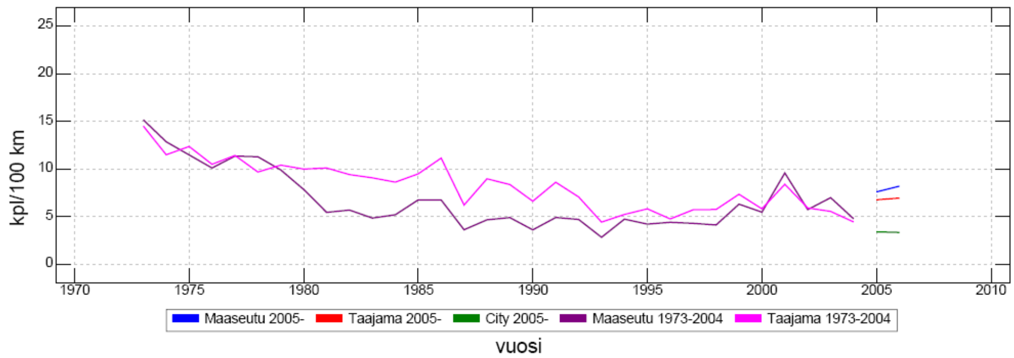



Figure 13. Statistics from Finnish energy industries on permanent faults

### *4.1.2 High-speed auto-reclosings*

When fault happens, protection drives switchgear and breaks the circuit in order to let fault disappear by its own, and shortly after (~ 0.2 s) energizes the system again. This is high-speed reclosing. Most often after this operation fault is removed and feeder works in normal mode.

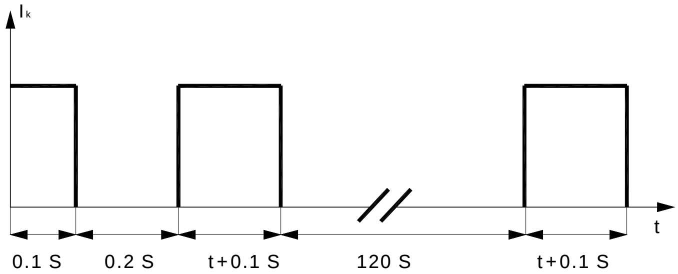



Figure 14. Autoreclosing cycle in permanent fault

Significant part (in rural areas – major part) of faults is non-permanent faults and can be removed by auto-reclosing operations, as can be seen from Figure 15 and Figure 16. That means reasonableness of implementing such automation in protection schemes of distribution networks.

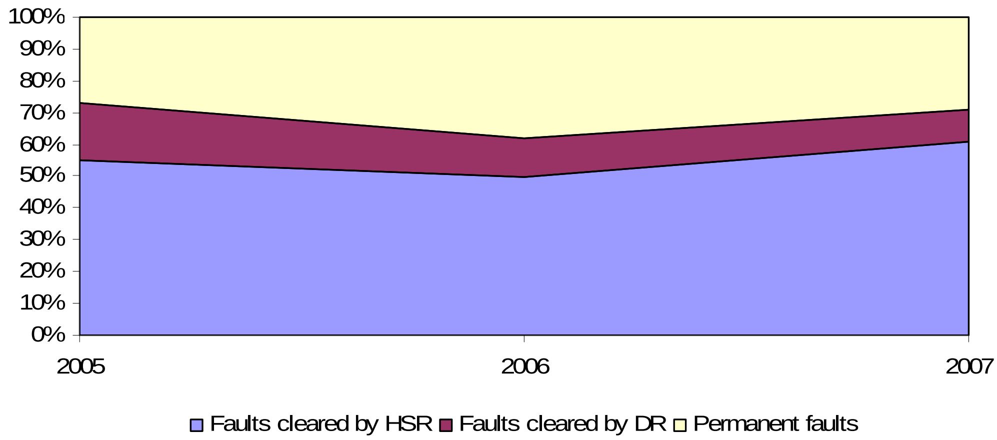



Figure 15. Finnish Energy Industries statistics on types of faults in rural areas

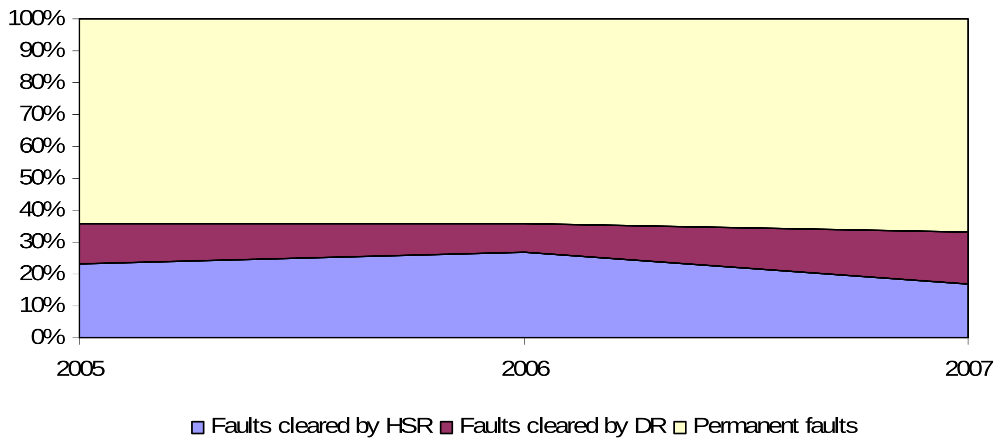



Figure 16. Finnish Energy Industries statistics on types of faults in city areas

### *4.1.3 Delayed auto-reclosings*

Sometimes, when single reclosing cycle is insufficient for removal of the fault, delayed reclosings are used. Circuit breaker opens again, for longer period of time (~ 2 min) and then closes. Typical number of delayed autoreclosings for overhead line structure is 5-15 pcs./100km,a.

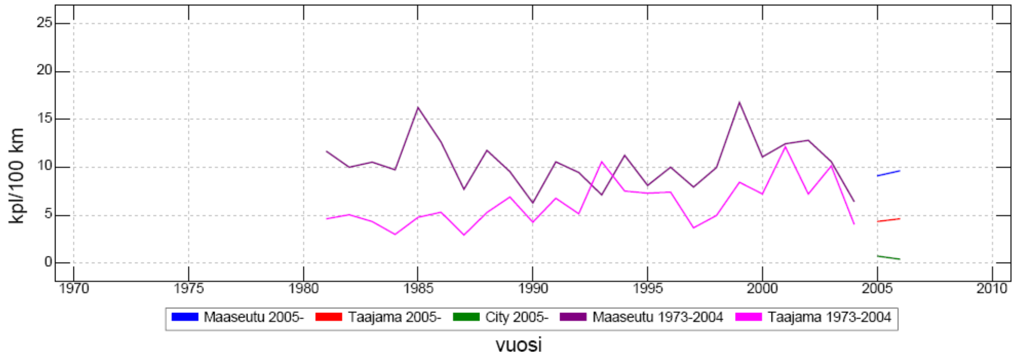



Figure 17. Statistics from Finnish energy industries on non-permanent faults

### *4.1.4 Planned outages*

Planned outage is scheduled maintenance of part of the system. Necessary preparations are made, and then necessary operations performed, while part under maintenance is disconnected from the system.

### *4.1.5 Interruption frequencies*

In this work fault rates are taken from the long run reliability statistics reports of Finnish energy industry. They are for permanent faults 5 faults/100km,a, for planned interruptions 3 interruptions/100km,a, for high-speed reclosings 10 interruptions/100km,a and for delayed reclosings 30 interruptions/100km,a. These values describe typical rural area distribution network environmant.

## 4.2 Operational parameters

Depending on the disconnector and switchgear placement, restoration of the certain part of the feeder can take different time. In this work following values assumed constant. Values, which are used in the calculations are for repairing 2 hours, for manually controlled disconnector switching 1 hour and for remote controlled disconnector switching 10 min.

## 4.3 Development of the model

Requirements for the reliability model have been set: the model should calculate reliability indices and outage costs (total and each component separately) for radial feeder with one backup connection at the end or without backup connection, without branch lines, with free placement of disconnectors and reclosers.

Also, theoretical study using development model had to be made to show and analyse the process of determining the optimal placement of disconnecting devices at the feeder and to analyse sensitivity of results to variation of input data.

### *4.3.1 Calculation principles*

To derive principal equations for writing calculation program, theorethical case feeder was considered (Figure 18).

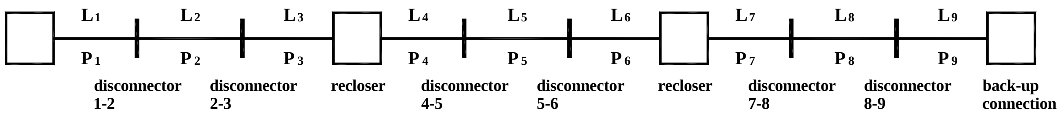



Figure 18. Example of feeder structure

Backup connection can be done using switchgear, manual- or remote-controlled disconnector. Also, a case without backup connection was studied. Generally speaking, equation for outage costs parameters for every feeder section can be expressed as shown in Equation (7).

$$C_{ij} = f_i \cdot P_j \cdot (X_j \cdot Ce_i + Y_j \cdot Cp_i) \tag{7}$$

where

| | |
|---|---|
| $C_{ij}$ | outage costs for feeder section *j* for outages of type *i* |
| $f_i$ | outage frequency for outages of type *i* |
| $P_j$ | average power consumed at feeder section *j* |
| $Ce_i$ | unit outage cost for outages of type *i*, [€/kWh] |
| $Cp_i$ | unit outage cost for outages of type *i*, [€/kW] |

$X_j = L_j \cdot T_k + .. + L_q \cdot T_p$, $Y_j = L_j + .. + L_q$ multipliers, dependent on construction of feeder, where

| | |
|---|---|
| $L_j$ | length of the feeder section *j* |
| $T$ | disconnection time or repair time. |
| $Y_j$ | can be obtained by excluding times from $X_j$. |

For given feeder, for permanent faults:

$$X_1 = L_1 \cdot T_R + L_2 \cdot T_{12} + L_3 \cdot min(T_{12}, T_{23}) \quad (8)$$

$$X_2 = L_2 \cdot T_R + L_3 \cdot T_{23} + L_1 \cdot max(T_{12}, T_{BU}) \quad (9)$$

$$X_3 = L_3 \cdot T_R + L_2 \cdot max(T_{23}, T_{BU}) + L_1 \cdot max(min(T_{12}, T_{23}), T_{BU}) \quad (10)$$

$$X_4 = L_4 \cdot T_R + L_5 \cdot T_{45} + L_6 \cdot min(T_{45}, T_{56}) + (L_1 + L_2 + L_3) \cdot T_{BU} \quad (11)$$

$$X_5 = L_5 \cdot T_R + L_6 \cdot T_{56} + L_4 \cdot max(T_{45}, T_{BU}) + (L_1 + L_2 + L_3) \cdot T_{BU} \quad (12)$$

$$X_6 = L_6 \cdot T_R + L_5 \cdot max(T_{56}, T_{BU}) + \\ + L_4 \cdot max(min(T_{45}, T_{56}), T_{BU}) + (L_1 + L_2 + L_3) \cdot T_{BU} \quad (13)$$

$$X_7 = L_7 \cdot T_R + L_8 \cdot T_{78} + L_9 \cdot min(T_{78}, T_{89}) + (L_1 + ... + L_6) \cdot T_{BU} \quad (14)$$

$$X_8 = L_8 \cdot T_R + L_9 \cdot T_{89} + L_7 \cdot max(T_{78}, T_{BU}) + (L_1 + ... + L_6) \cdot T_{BU} \quad (15)$$

$$X_9 = L_9 \cdot T_R + L_8 \cdot max(T_{89}, T_{BU}) + \\ + L_7 \cdot max(min(T_{78}, T_{89}), T_{BU}) + (L_1 + ... + L_6) \cdot T_{BU} \quad (16)$$

where

$T_R$ repair time
$T_{MN}$ disconnection time for disconnector between sections *m* and *n*
$T_{BU}$ time, required for connection to backup source of energy.

Time required for connection to backup source of energy is dependent on type of switching device installed at connection point. For remote- or manual-controlled disconnector it is their disconnection times respectively, for recloser it is equal to zero. If there is no backup connection, we can replace $T_{BU}$ with $T_R$ in all equations and get correct results.

As can be noticed from these equations, there is a common logic in them and it is possible to create a single algorithm for calculating outage costs for any configuration of such kind of feeder without branches. From the section under consideration, it is needed to go both directions (to the supply and to the backup connection), and check, which devices are in the way, what is the fastest way to restore electricity supply, and use appropriate times. Simplified flowchart of algorithm, used in the model for calculating outage costs caused by permanent faults is presented in Figure 19.

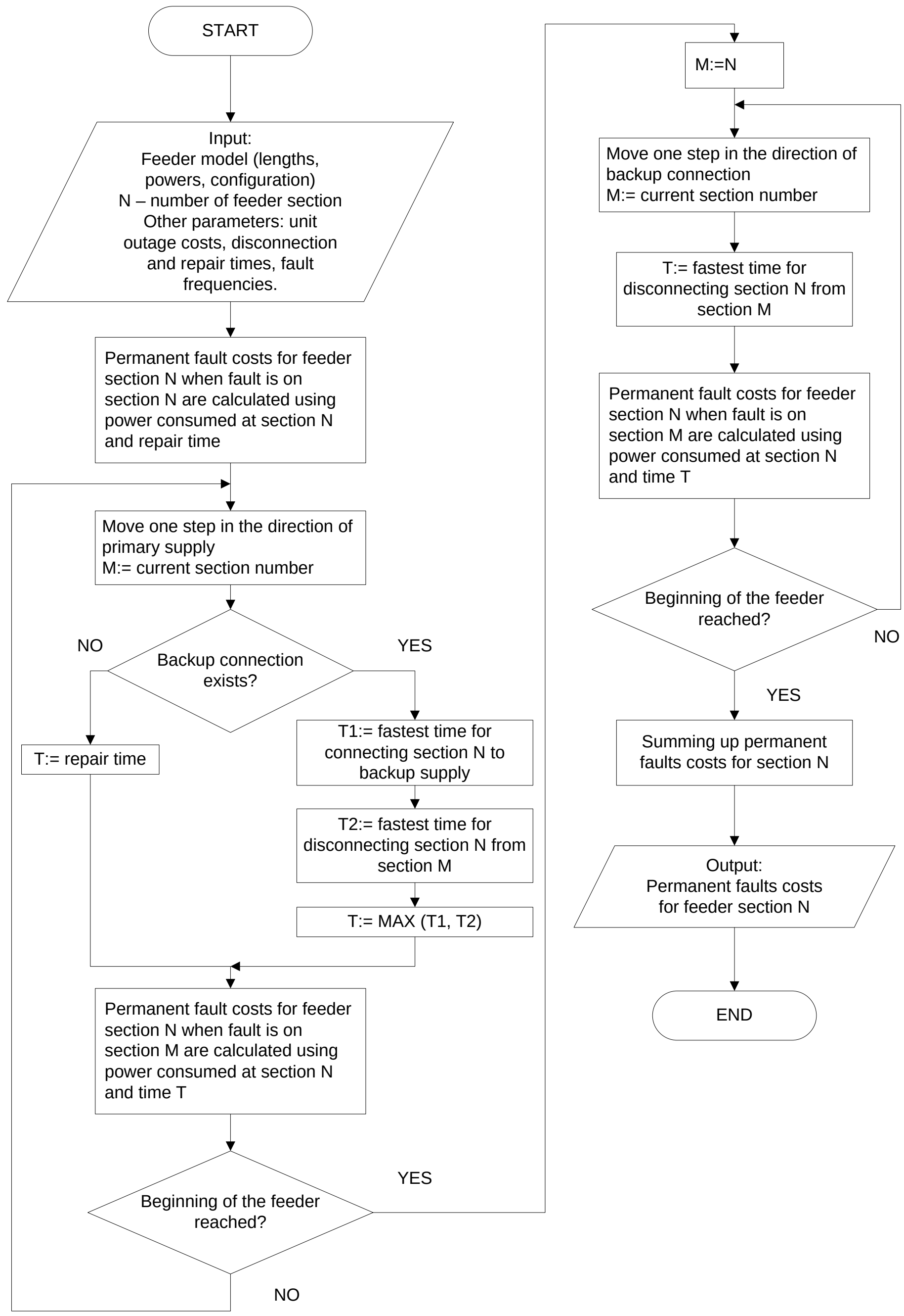



Figure 19. Flowchart for calculating permanent faults costs

Calculation algorithms for other fault types differ from the one presented in the flowchart.

For planed outages:

With backup

$$X_1 = L_1 \cdot T_\mathrm{R}$$
$$X_2 = L_2 \cdot T_\mathrm{R} \qquad (17)$$
$$...$$
$$X_9 = L_9 \cdot T_\mathrm{R}$$

No backup

$$X_1 = L_1 \cdot T_\mathrm{R}$$
$$X_2 = (L_1 + L_2) \cdot T_\mathrm{R} \qquad (18)$$
$$...$$
$$X_9 = (L_1 + L_2 + ... + L_9) \cdot T_\mathrm{R}$$

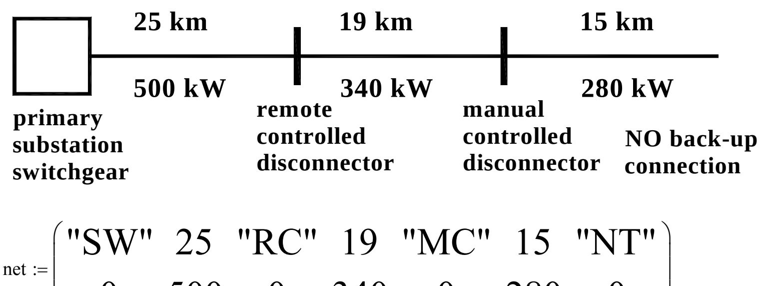
For high-speed and delayed reclosings, $X = 0$,

$$Y_1 = L_1 + L_2 + L_3 = Y_2 = Y_3$$
$$Y_4 = L_4 + L_5 + L_6 = Y_5 = Y_6 \qquad (19)$$
$$Y_7 = L_7 + L_8 + L_9 = Y_8 = Y_9$$

Program for calculations has been written in mathematical software Mathsoft Mathcad.

### 4.3.2 Input data and results

Input data consists of fault frequencies, unit outage costs, repair and disconnection times, and feeder configuration. Feeder configuration is defined by ($2N$+1, 2)-sized matrix, where $N$ – is number of feeder sections. Disconnectors, switches and backup connection type are described in matrix using reference characters. Length of the feeder section in km and power consumed on it in kW are also in the matrix. Example of feeder and its matrix representation is shown in the Figure 20.




$$\mathrm{net} := \begin{pmatrix} \text{"SW"} & 25 & \text{"RC"} & 19 & \text{"MC"} & 15 & \text{"NT"} \\ 0 & 500 & 0 & 340 & 0 & 280 & 0 \end{pmatrix}$$

Figure 20. Example of feeder configuration and its matrix representation for reliability model

Results displayed after calculations are outage costs for permanent faults and planned outages, divided into duration-dependent and frequency-dependent portions, and total; high-speed and delayed reclosings costs, total outage costs, reliability indices (SAIFI, SAIDI, MAIFI). Reliability indices are calculated out of outage costs, assumed that power is equally distributed between the customers and each customer has 1 kW average consumption.

$$\mathrm{SAIDI}=\frac{C\mathrm{e}_{\mathrm{PF}}}{\mathrm{Ce}_{\mathrm{0PF}}\cdot P_{\mathrm{T}}} \tag{20}$$

$$\mathrm{SAIFI}=\frac{C\mathrm{p}_{\mathrm{PF}}}{\mathrm{Cp}_{\mathrm{0PF}}\cdot P_{\mathrm{T}}} \tag{21}$$

$$\mathrm{MAIFI}=\frac{\dfrac{C_{\mathrm{HSR}}}{\mathrm{C}_{\mathrm{0HSR}}}+\dfrac{C_{\mathrm{DR}}}{\mathrm{C}_{\mathrm{0DR}}}}{P_{\mathrm{T}}} \tag{22}$$

where

| | |
|---|---|
| $C\mathrm{e}_{\mathrm{PF}}$, $C\mathrm{p}_{\mathrm{PF}}$ | total outage costs for permanent faults dependent on duration and on frequency of faults respectively |
| $C\mathrm{e}_{\mathrm{0PF}}$, $C\mathrm{p}_{\mathrm{0PF}}$ | unit outage costs for permanent faults dependent on duration and on frequency of faults respectively |
| $C_{\mathrm{HSR}}$, $C_{\mathrm{DR}}$ | total outage costs for high-speed and delayed reclosings respectively |
| $C_{\mathrm{0HSR}}$, $C_{\mathrm{0DR}}$ | unit outage costs for high-speed and delayed reclosings respectively |
| $P_{\mathrm{T}}$ | total power through the feeder. |

Also, results for each specific feeder section can be calculated, if needed.

### *4.3.3 Note about model simplification*

In the developed model assumption is made that all circuit breakers and reclosers operate simultaneously and immediately. But in real life situation is different. In the case when backup connection device is recloser and there are reclosers in the feeder, increase of momentary interruptions number is observed. Example of such case is shown in Figure 21.

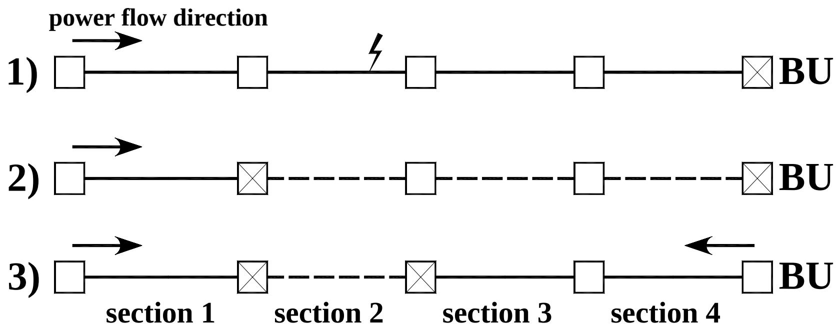



Figure 21. Sequence of switch states during the fault at feeder section 2

When the fault happens on the feeder section 2, recloser between sections 1 and 2 opens first. Now faulted section is isolated. This causes a momentary interruption for customers, which get electricity from sections 3 and 4. Then, recloser between sections 2 and 3 is opened and backup connection recloser is closed. For feeder structure in this example, additional momentary outage costs constitute about 2 % of total outage costs, as following calculations show.

Assumption: feeder is 50 km long, average power is 1000 kW, evenly distributed along the feeder. There are 4 reclosers in the feeder, as shown in Figure 21. Fault frequencies and durations, outage cost parameters values which are described before, are used in calculation. Total outage costs calculated using model are 46500 €/a.

Additional outage costs due to momentary interruptions.

$$C_{ADD} = f_{PF} \cdot C_{HSR} \cdot (L_1 \cdot (P_2 + P_3 + P_4) + L_2 \cdot (P_3 + P_4) + L_3 \cdot P_4) \tag{23}$$

where

$f_{PF}$ frequency of permanent faults;
$C_{HSR}$ outage cost parameter for high-speed reclosings.

$C_{ADD}$ = 993.75 €/a and $\frac{993.75}{46500} \cdot 100\% = 2.1\%$.

Because of significant model complication is needed to take these additional costs into account, they are neglected in the developed model.

## 4.4 Feeder description

In these studies properties of developed calculation tool is shown by the theoretical case feeder. Feeder is 50 km long, starting at 110/20 kV primary substation. Total average load of the feeder is 1 000 kW, evenly distributed along the feeder. Backup connection is designed as remote-control disconnector, normally open. Possible places for disconnectors and reclosers are at every 5 km. Total costs are calculated as total outage costs added with equipment annuity. Outage cost structure for feeder is shown in Figure 22. Annuity of equipment shown in the figure is backup connection RCD annuity.

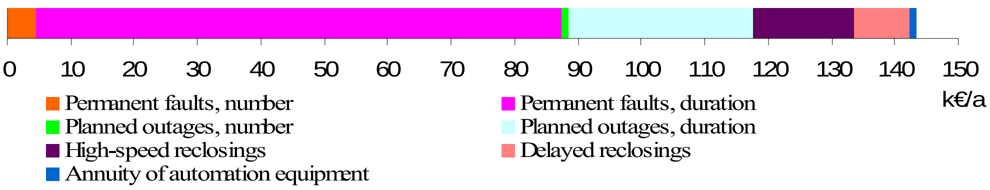



Figure 22. Costs structure for feeder with no automation installed

## 4.5 Installation of manually controlled disconnectors

In this theoretical study it is assumed that all automation equipment is installed at the feeder in one step. For each quantity of switching devices their optimal placement is different. Optimal placement of manually controlled disconnectors for each case, from 1 to 9 disconnectors, is shown in Figure 23.

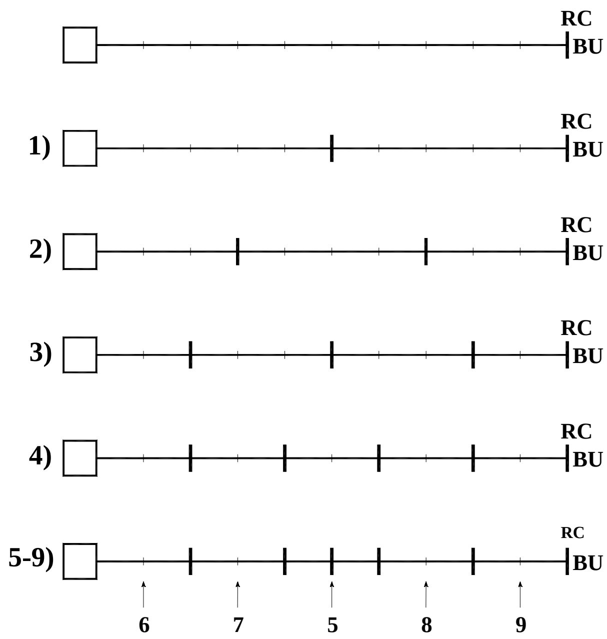



Figure 23. Order of manually controlled disconnectors installation

Figure 24 shows decrease in total costs and SAIDI. It can be seen from the figure that first disconnectors give the most effect.

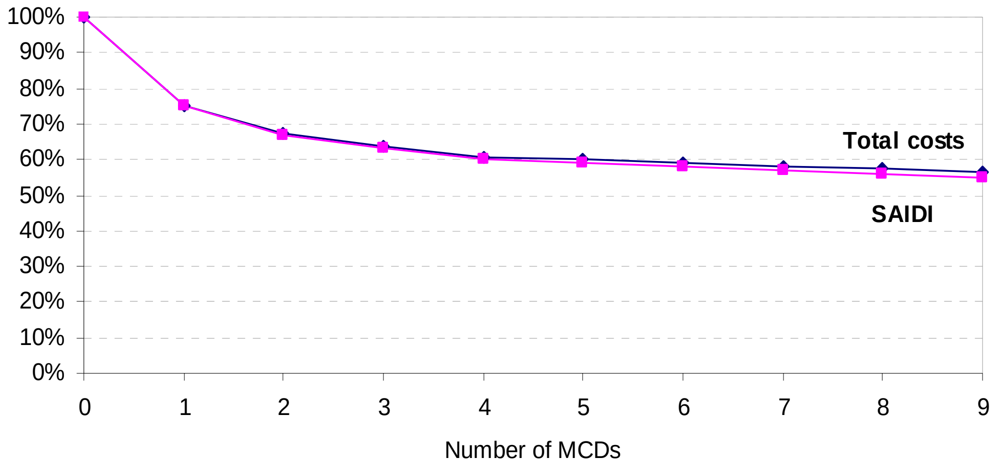



Figure 24. Infulence of MCDs on SAIDI and total costs

Figure can be used to find out the decrease in SAIDI and outage costs, but to determine is the investment profitable or not, final economic benefit has to be found out by comparing amount of investment to outage cost benefits. Price of disconnector needs to be converted to annuity to compare with outage costs benefit.

Interest rate $P = 5\ \%$

Disconnector lifetime $T = 25$

Disconnector investment 3500 € (EMA)

Annuity

$$a = \varepsilon \cdot C_{\mathrm{MCD}} = \frac{P}{1 - \dfrac{1}{(1+P)^{\tau}}} \cdot C_{\mathrm{MCD}} \tag{24}$$

$$a = \frac{0.05}{1 - \dfrac{1}{(1+0.05)^{25}}} \cdot 3500 = 248.5\ \text{€/a}$$

Results of comparison investments annuity with benefits they give are shown in the Figure 25. Level of 100 % corresponds to the situation when investment annuity is equal to outage costs benefit. Also, profitability of investments curves are shown for 1500 kW and 750 kW total average loads.

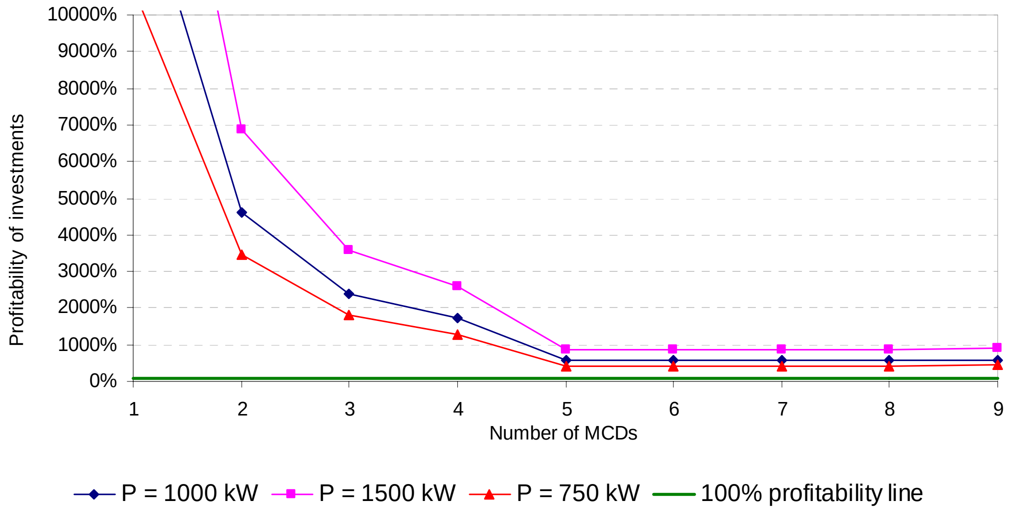



Figure 25. Profitability of investments depending on average power of the feeder.

From the figure 25 it can be seen that it is profitable to install 9 MCDs (for all three variants of feeder power). Then, total costs are decreased by 47 %, from 143 500 €/a to 81 160 €/a, SAIDI decreased by 55, from 5 h/a to 2.75 h/a. Costs structure diagram after installing 9 MCDs is shown in Figure 26.

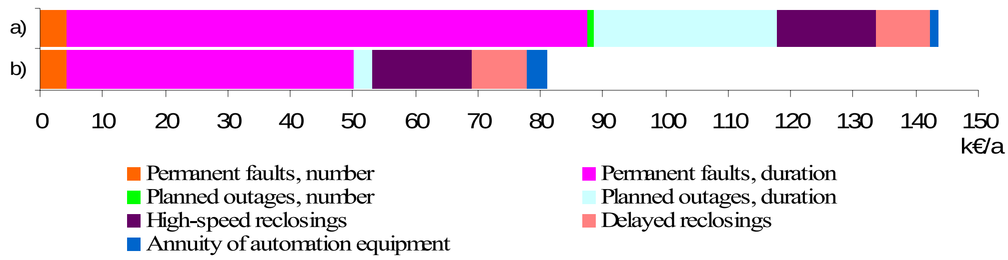



Figure 26. Costs structure when a) no switching equipment installed and b) 9 MCDs installed.

As it can be seen from the diagram, contribution of permanent faults lowered significantly, planned outages costs decreased 10 times, reclosings costs remain the same (compared to feeder without switching equipment).

### *4.5.1 Results analysis*

Most benefit comes from installing several first disconnectors. But installing manual disconnectors in every position is beneficial in our case. Equality of results for disconnectors 5-9 is explainable. From reliability point of view, when there are four disconnectors installed, feeder is divided to five equal parts, and installation of each new disconnectors just divides these parts into smaller ones, with no effect to the rest of feeder, giving the same benefit in annual outage time and, therefore, in outage costs. For each number of disconnectors installed, optimal placement of them varies. If we would be able to place disconnectors at any point of the feeder, optimal results would always be achieved, when disconnectors divide feeder to equal parts.

## 4.6 Installation of remote controlled disconnectors

In the beginning, there are 9 MCDs installed. They are replaced them one by one with remote controlled disconnectors in the same order, like installation of MCDs has been made. Investment cost of RCD in these studies is 15 920 € (EMA), which is 1 130 €/a ($p$ = 5 % and $t$ = 25 a). Figure 27 shows results of the calculations.

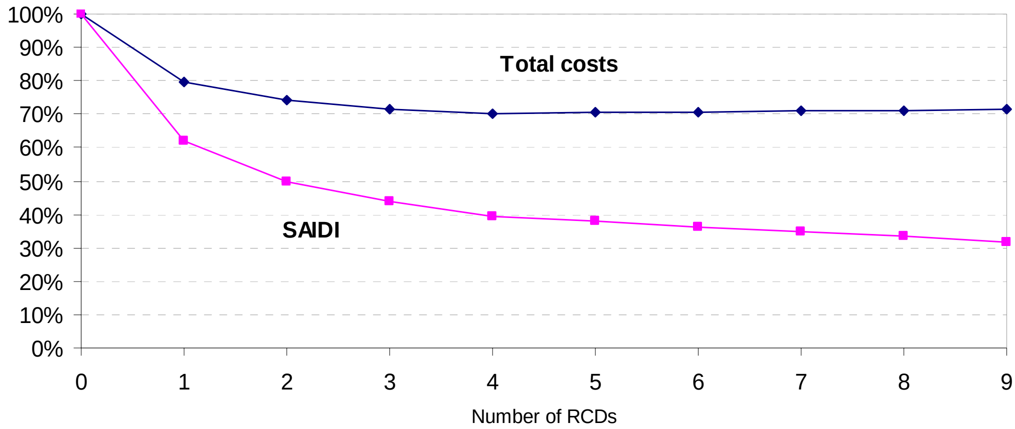



Figure 27. Influence of RCDs on SAIDI and total costs. Level of 100 % illustrates situation before automation installation.

In this figure 100 % values correspond to feeder with 9 MCDs already installed. It can be seen that after four RCDs costs curve goes up, which means, that there are no economic incentives to install more than four RCDs. Results of profitability analysis are shown in Figure 28.

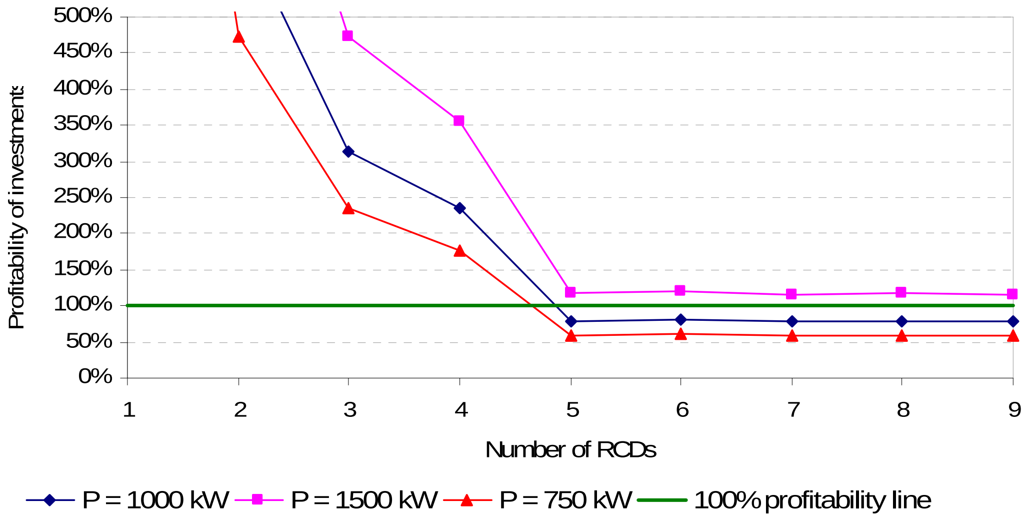



Figure 28. Profitabiliy of investments depending on average power of the feeder.

From the Figure 28 it can be seen, that it is profitable to install four MCDs (for 750 kW and 1000 kW, for 1500 kW it is profitable to replace all MCDs with RCDs). Then, total costs are decreased by 30 % from 81 160 €/a to 57 940 €/a, SAIDI decreased by 61 % from 2.75 h/a to 0.875 h/a (compared to feeder with 9 MCDs installed).

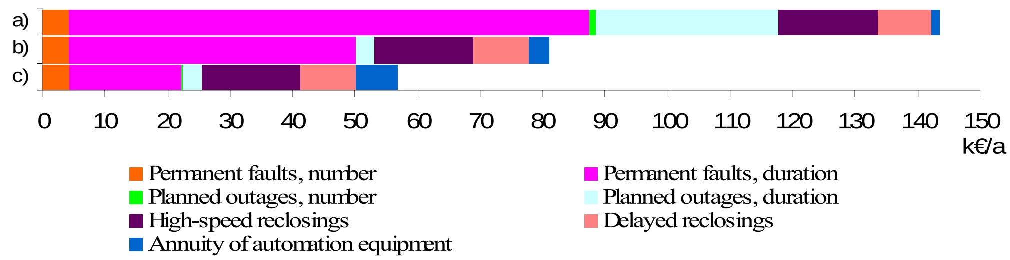



Figure 29. Costs structure of case feeder when a) switching equipment installed; b) 9 MCDs installed; c) 5 MCDs and 4 RCDs are installed.

Figure 29 shows that only outage costs corresponding to permanent faults duration are reduced compared to feeder with MCDs.

### *4.6.1 Results of analysis*

Again, most benefit comes from installing several first disconnectors. Remote controlled disconnectors are significantly more expensive than MCDs and it can be seen, that installing five or more disconnectors lead to increase in total costs, because annuity of new disconnector is more than benefit it gives. Equality of results for disconnectors 5-9 is has the same explanation, as for MCDs. RCDs affect system SAIDI significantly, because difference between manual disconnection time and time of remote controlled disconnection is considerable.

## 4.7 Installation of reclosers

Next, there are 9 MCDs installed. They are replaced one by one with reclosers in the order shown in the Figure 30. Each time when new recloser added, configuration of the feeder switching equipment needed for most effective performance is different.

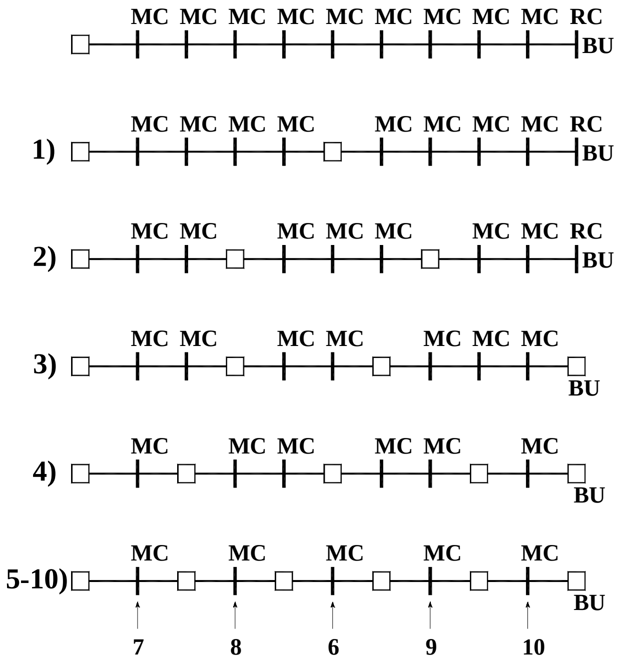



Figure 30. Order of installation of reclosers

Price of pole-mounted recloser in these studies is 21 230 € (EMA), which is 1 507 €/a ($p$ = 5 % and $t$ = 25 a)

Calculation results are shown in Figure 31, and include SAIFI, because reclosers affect interruption frequency in the part of the system they protect:

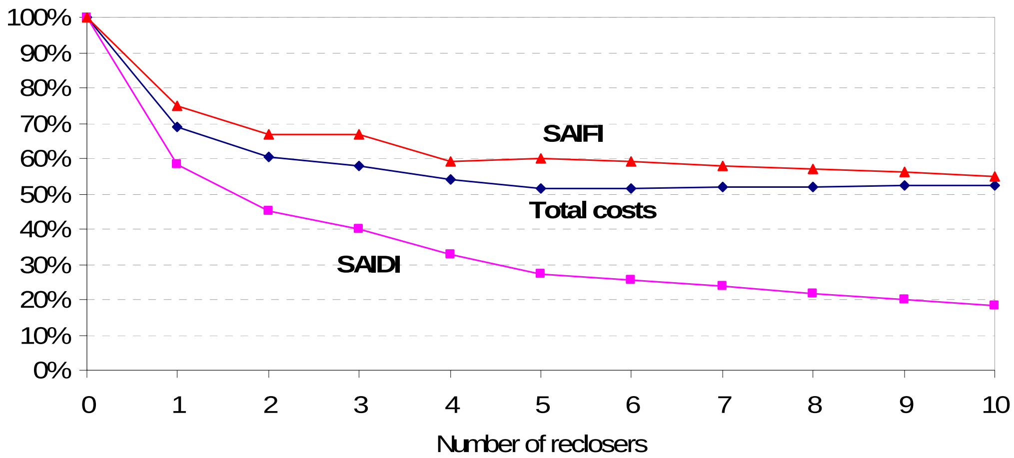



Figure 31. Influence of reclosers on SAIDI, MAIFI and total costs.

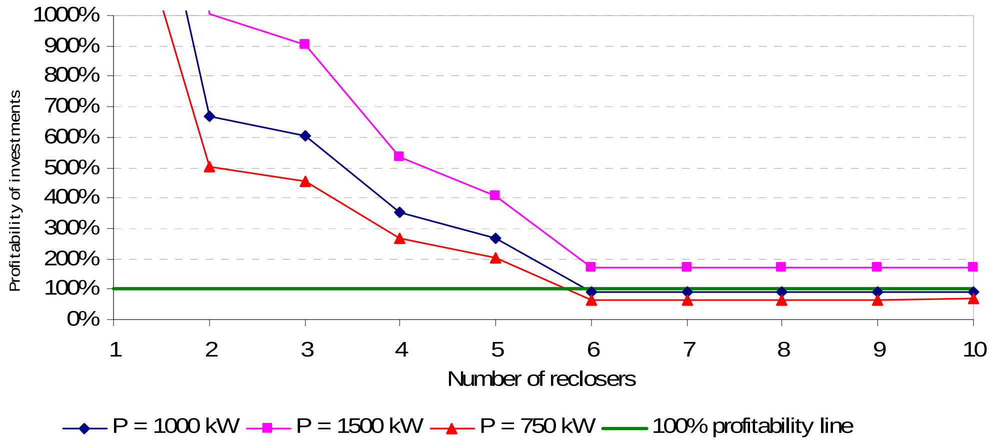



Figure 32. Profitabiliy of investments depending on average power of the feeder.

From the Figure 32 it can be seen, that it is profitable to install five reclosers (for 750 kW and 1000 kW, for 1500 kW it is profitable to replace all MCDs with reclosers). Then, total costs are decreased by 48 % from 81 160 €/a to 41 680 €/a, SAIDI decreased by 82 % from 2.75 h/a to 0.75 h/a, MAIFI (and SAIFI) decreased by 40 % (compared to feeder with 9 MCDs).

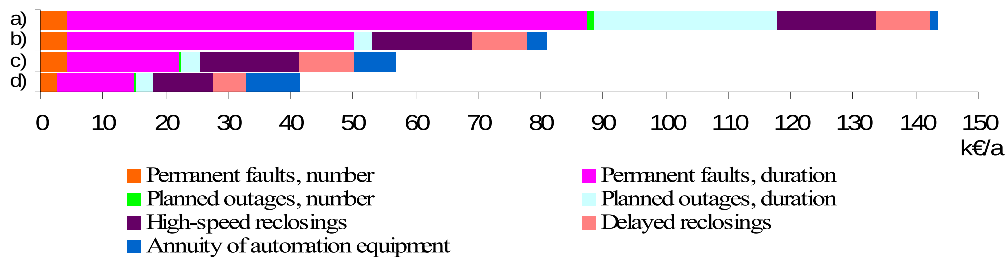


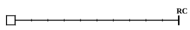
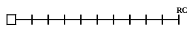
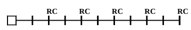

Figure 33. Costs structure of case feeder when a) no switching equipment installed; b) 9 MCDs installed; c) 5 MCDs and 4 RCDs installed; d) 5 MCDs and 5 reclosers installed

### *4.7.1 Results of analysis*

As expected, first reclosers are the most beneficial investment. Reclosers reduce SAIFI and MAIFI because they make possible isolating the fault without disconnecting the whole feeder. Price difference between remote controlled disconnectors and reclosers is much less than difference in benefits they give, and it can be said, that when it is beneficial to install a RCD in some place, it is more beneficial to install a recloser here.

Results of implementing feeder automation for 1 000 kW average power is shown in the Table 4.

Table 4. Reliability results. Total costs include annuity of the investments and annual outage costs.

| Feeder configuration | Initial  | MCDs  | RCDs  | Reclosers  |
|---|---|---|---|---|
| Total costs, €/a | 143 500 | 81 160 | 56 990 | 41 680 |
| Total costs, % | 100 % | 57 % | 40 % | 29 % |
| Outage costs, €/a | 142 370 | 77 800 | 50 100 | 32 930 |
| Outage costs, % | 100 % | 55 % | 35 % | 23 % |
| SAIDI, hr/a | 5.00 | 2.75 | 1.08 | 0.75 |
| SAIDI, % | 100 % | 55 % | 22 % | 15 % |
| SAIFI, faults/a | 2.50 | 2.50 | 2.50 | 1.50 |
| SAIFI, % | 100 % | 100 % | 100 % | 60 % |
| MAIFI, faults/a | 20.0 | 20.0 | 20.0 | 12.0 |
| MAIFI, % | 100 % | 100 % | 100 % | 60 % |

## 4.8 Sensitivity of results to the variation of input data

Feeder outages are of random character, it is impossible to predict exact number of outages that will happen in certain year. Also, some inaccuracies in determining restoration times and other parameters practically always exist, because practically all parameters, which are used for reliability calculations are constantly changing, except values like feeder length. Some information may be missing or difficult to obtain, and in such cases we have to use approximate values or values from sources irrelevant to case. This causes variations of results, and it is necessary to be able to predict and evaluate such effects.

In the Figure 34 there is varied operation time of remote controlled disconnector from 5 minutes to 15 minutes.

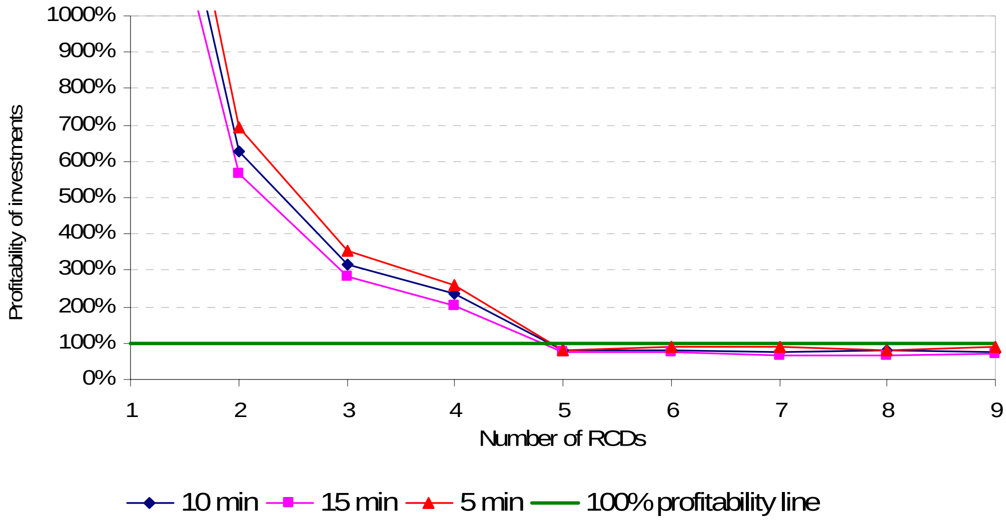



Figure 34. Dependence of RCDs profitability on variation of RCD disconnection time.

For instance, with three RCDs annual total costs are 58 190 €/a when operation time is 10 min. If operation time is 5 min, annual total costs are 55 610 €/a, and with 15 min total costs are 60710 €/a, but investment annuity is the same in all three cases. Level of 100 % means that benefit in outage costs is equal to the price of investment.

In the Figure 35 effect of variation of interest rate from 3 to 8 % is shown.

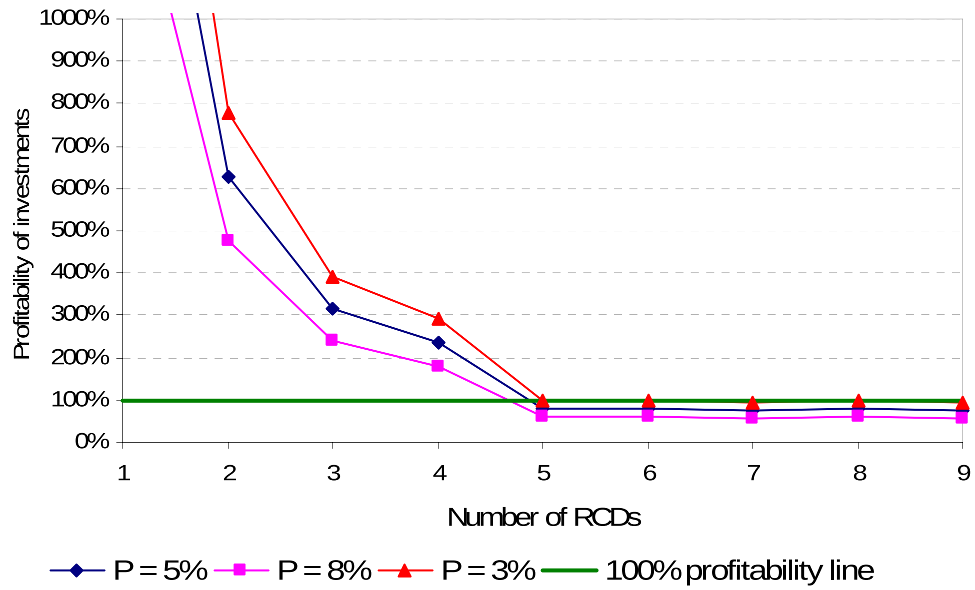



Figure 35. Dependence of RCDs profitability on variation of interest rate

Fault frequencies vary from year to year, as can be seen from paragraph 4.1. In the Figure 36 effect of variation of fault rates from is shown.

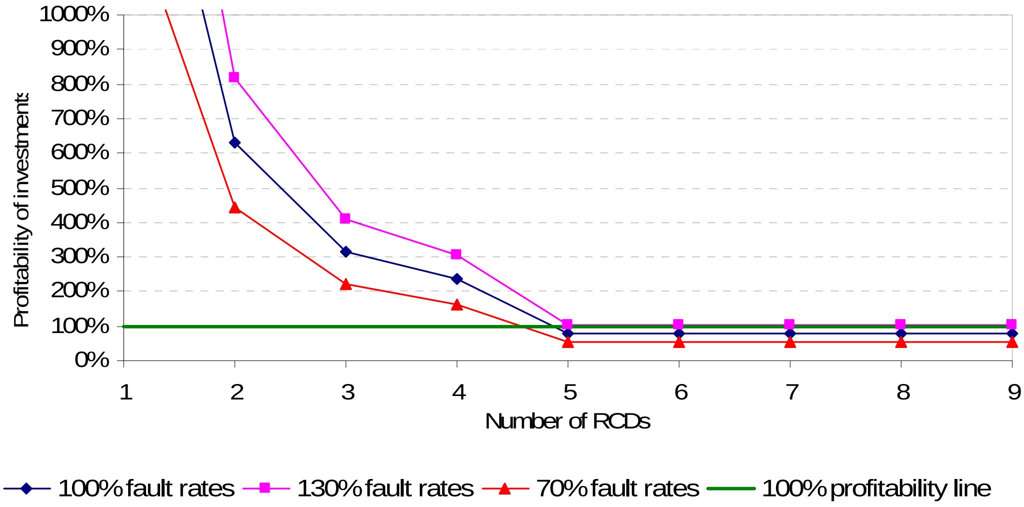



Figure 36. Dependence of RCDs profitability on variation of fault frequencies. 100 % corresponds to values given in Paragraph 4.1.5

Because of varying conditions, such as climate, age and type of components, it is important that the utilities have their own good quality statistics. Variations of input parameters have significant effect on results of reliability calculations. But uncertainties concerning outage costs should not prevent utilities from planning of network renovation. Sensitivity analysis is easy to perform using available planning tools (Sand et al. 1989).

## 4.9 Further development of the model

Beyond this diploma work, this program has several possibilities for further extensive development. It is possible to create algorithm that calculates outage costs for feeder of complex structure (with branch lines, loops, etc). It requires different representation of feeder in the model, for example, matrix, which stores information about interconnections between sections and another matrix which stores information about each specific section (length, power, number of customers, etc). For example, one method described before is to use RITM (repair and isolation time matrix). RITM is a square matrix, dimensioned $N \times N$, consisting of $X_{ij}$ elements, where $N$ is number of feeder sections and $Xij$ is the outage time for section j when there is a fault on section i (Zou et al. 2007). But the main problem to be solved is automatic generation of RITM for the feeder of random configuration.

Different outage statistics for different parts of feeder can be useful. For example, if part of the feeder is overhead line and the rest is underground cable or line location differs from each others (field area vs. forest areas). Also, model should take into account real number of customers on each specific section in order to calculate reliability indices correctly.

Single-phase operation/single-phase lockout and single-phase operation/triple-phase lockout operation modes for reclosers can be implemented, as well as other qualities and capabilities of network equipment. The next step – is automatic optimization of placement of disconnectors, sectionalizers and reclosers for acquisition of the most cost-effective solution for the case (taking into account cost of the equipment, interest rates, etc). Then - analysis of sensitivity of the solution to uncertainty of input data and possible future increase of loads. Graphical interface, visualization of the solution, topographical view of the feeder, etc. Finally, integration with other programs, which use industrial file standards.

# 5 Case study

Case feeder is the part of 20 kV distribution network situated in the southern part of Finland. It is operated by Etelä-Suomen Energia Oy. Total length of feeder is a little bit over 40 km and average power 1900 kW. There are two backup connections. In the analysis it is assumed that all the power needed on the feeder can be delivered through the backup connections if needed. This is not necessarily the situation in real life especially in rural areas where distances are extensive and voltage rigidity is weak. Fault rates assumed to be constant through the whole feeder. Automatic reclosers and circuit breakers assumed to be properly coordinated in order to isolate faulted section in the optimal way.

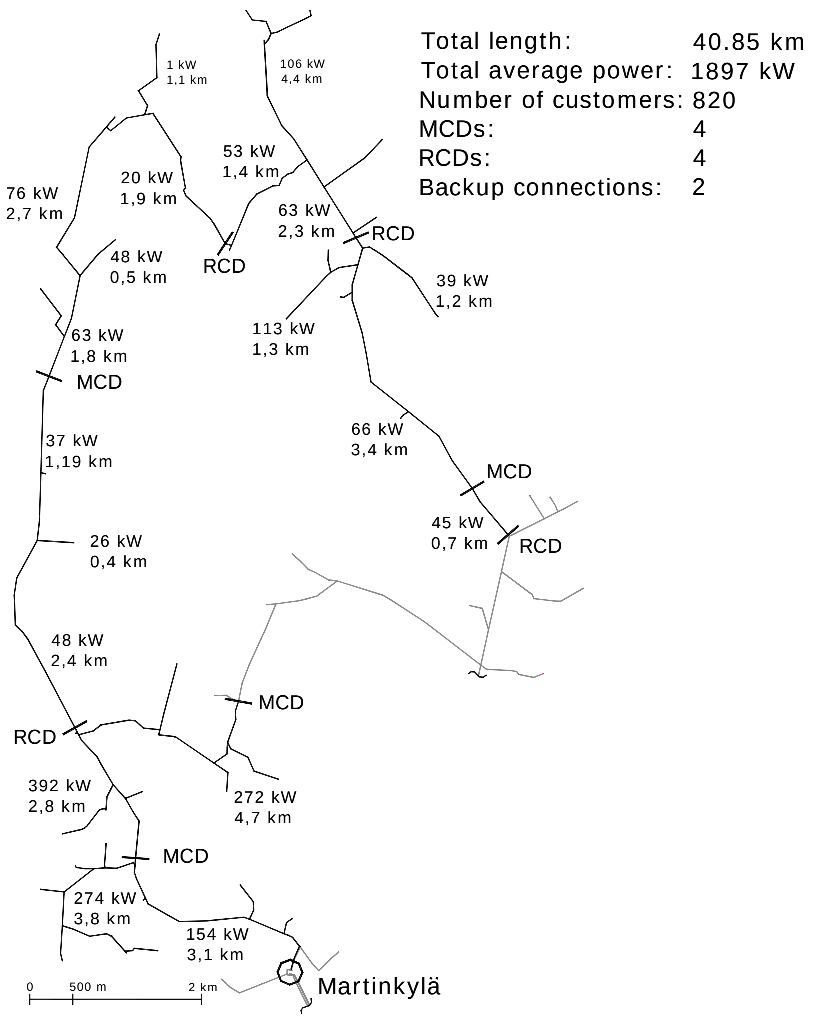



Figure 37. Case feeder. MCD stands for manual controlled disconnector and RCD for remote controlled disconnector.

## 5.1 Preparing the case feeder data into calculation model

Because calculation model does not support feeders with branch lines, feeder structure has to be simplified. Branch lines, which are not separated from the main feeder with disconnectors from reliability point of view are inseparable from the feeder section which they are connected to. In case of fault, they are disconnected and reconnected together. Thus, it is possible to remove branch lines of this kind just by summing up their lengths and powers with corresponding feeder sections. Result of simplification is shown in the Figure 38.

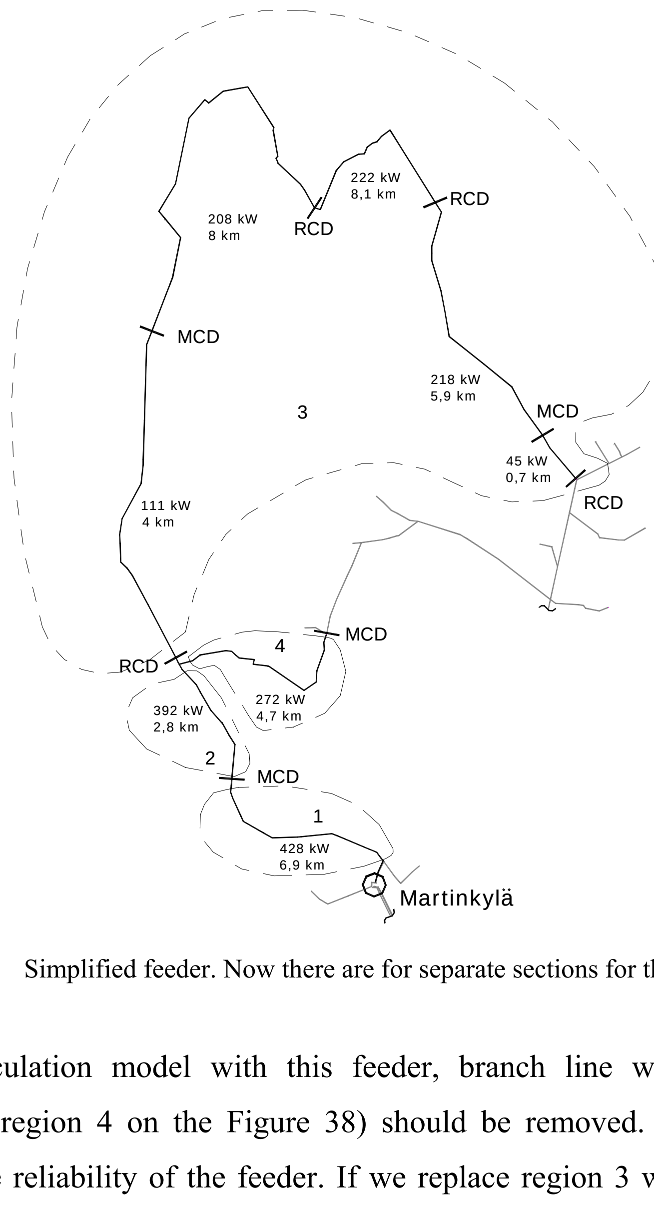



Figure 38. Simplified feeder. Now there are for separate sections for the analysis.

To use calculation model with this feeder, branch line with MCD backup connection (region 4 on the Figure 38) should be removed. Let’s consider its effect on the reliability of the feeder. If we replace region 3 with sum of power consumed in it and sum of feeder lengths, we obtain structure, which is presented in Figure 39.

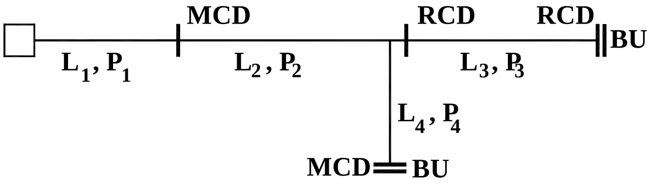



Figure 39. Simplified feeder model

Expressions for permanent faults costs of this feeder are shown in equations (25-28).

$$C_1 = f_{PF} \cdot P_1 \cdot (L_1 \cdot (Cp_{PF} + T_R \cdot Ce_{PF}) + (L_2 + L_4) \cdot (Cp_{PF} + T_{MCD} \cdot Ce_{PF}) + L_3 \cdot (Cp_{PF} + T_{RCD} \cdot Ce_{PF}))$$
$$C_2 = f_{PF} \cdot P_2 \cdot (L_1 \cdot (Cp_{PF} + T_{MCD} \cdot Ce_{PF}) + (L_2 + L_4) \cdot (Cp_{PF} + T_R \cdot Ce_{PF}) + L_3 \cdot (Cp_{PF} + T_{RCD} \cdot Ce_{PF}))$$
$$C_3 = f_{PF} \cdot P_2 \cdot (L_1 \cdot (Cp_{PF} + T_{RCD} \cdot Ce_{PF}) + (L_2 + L_4) \cdot (Cp_{PF} + T_{RCD} \cdot Ce_{PF}) + L_3 \cdot (Cp_{PF} + T_R \cdot Ce_{PF}))$$
$$C_4 = f_{PF} \cdot P_4 \cdot (L_1 \cdot (Cp_{PF} + T_{MCD} \cdot Ce_{PF}) + (L_2 + L_4) \cdot (Cp_{PF} + T_R \cdot Ce_{PF}) + L_3 \cdot (Cp_{PF} + T_{RCD} \cdot Ce_{PF}))$$

As can be seen from the equations above, this backup connection has no effect on feeder reliability. Equations for sections 2 and 4 coincide (and this holds true for reclosings and planned outages), and we can replace these sections with sum of their powers and lengths.

After simplifications, we get feeder model, which is suitable for calculations using reliability model.

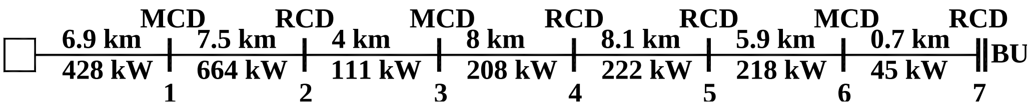



Figure 40. Feeder model

At the present situation, outage costs for the feeder based on developed model is shown in Figure 41. Total outage costs are 91 k€/a. Most of the cost are coming from permanent faults (duration) and from high-speed autoreclosings.

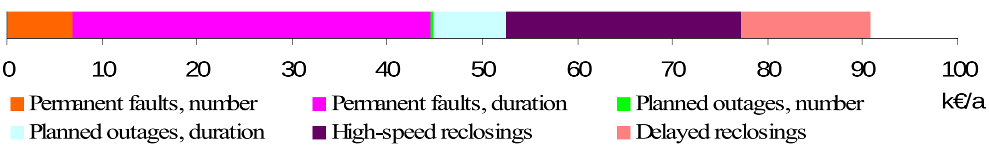



Figure 41. Outage costs of the case feeder before renovation.

## 5.2 Feeder automation renovation alternatives

The task is to find optimal renovation plan for the case feeder. There are two possible approaches presented in the study.

### *5.2.1 Step-by-step renovation*

In this approach existing switching equipment are replaced with new one-by-one. This may be useful when, for some reason, there is no possibility to buy all equipment at once, and it is planned to buy equipment in consecutive order. The main question is where the most beneficial place is for new disconnector or switching equipment and what it would be. In this study all the alternatives are analysed and done separately so that they do not have effect on each other. In the chapter 5.2.2 Single-step renovation feeder automation renovation is done as a whole the interdependences of reliability effects are taken into account.

First step of the renovation can be replacement of the MCD №1, №3 or №6 with RCD, or replacement of any disconnector with recloser. To find out, which solution is the most effective, comparison of their benefits is needed. Calculations are made with assumption that equipment, which is already installed in the feeder, is old and has no residual value.

Results of calculation are shown in Tables 5 and 6. When calculating reliability indices, it is assumed that number of customers is dependent linearly on power of each line section.

Table 5. Comparison of investments (replacement of MCDs with RCDs)

| Investment | No investment | $MCD_1$→ RCD | $MCD_3$→ RCD | $MCD_6$→ RCD |
|---|---|---|---|---|
| Outage costs, €/a | 90 970 | 85 580 | 89 780 | 90 680 |
| Investment annuity, €/a | 0 | 1130 | 1130 | 1130 |
| SAIFI, faults/a | 2.06 | 2.06 | 2.06 | 2.06 |
| SAIDI, hr/a | 1.20 | 1.03 | 1.16 | 1.19 |
| MAIFI, faults/a | 16.4 | 16.4 | 16.4 | 16.4 |
| Outage cost benefit, €/a | 0 | 5390 | 1190 | 290 |
| Savings, €/a | 0 | 4260 | 60 | -840 |

Table 6. Comparison of investments (replacement of MCDs and RCDs with reclosers)

| Investment | No investment | Rec.→ 1 | Rec.→ 2 | Rec.→ 3 | Rec.→ 4 | Rec.→ 5 | Rec.→ 6 | Rec.→ 7 |
|---|---|---|---|---|---|---|---|---|
| Outage costs, €/a | 90 970 | 75 040 | 69 980 | 70 120 | 76 040 | 83 210 | 89 750 | 90 970 |
| Investment annuity, €/a | 0 | 1 506 | 1 506 | 1 506 | 1 506 | 1 506 | 1 506 | 1 506 |
| SAIFI, faults/a | 2.06 | 1.67 | 1.29 | 1.34 | 1.51 | 1.77 | 2.02 | 2.06 |
| SAIDI, hr/a | 1.20 | 0.96 | 1.07 | 1.03 | 1.11 | 1.15 | 1.18 | 1.20 |
| MAIFI, faults/a | 16.4 | 13.4 | 10.3 | 10.7 | 12.1 | 14.2 | 16.2 | 16.1 |
| Outage cost benefit, €/a | 0 | 15 930 | 20 990 | 20 850 | 14 930 | 7 760 | 1 220 | 0 |
| Savings, €/a | 0 | 14 420 | 19 480 | 19 340 | 13 420 | 6 250 | -286 | -1 506 |

It can be seen from the table that the most effective investment at the first step is replacement of RCD2 with recloser, but placement recloser in the $3^{rd}$ positions gives practically the same results. In real life, some factor which is not discussed here can determine the choice between these two alternatives. In these studies replacement of RCD2 is selected as a first step. The next step is determined the same way, taking into account results of previous step. Results of calculation are shown in Table 7.

Table 7. Step-by-step renovation

| Step № | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Investment | - | Rec.→ 2 | Rec.→ 1 | Rec.→ 4 | Rec.→ 7 | Rec.→ 3 | Rec.→ 5 |
| Outage costs, €/a | 90 970 | 69 980 | 62 270 | 58 900 | 55 850 | 53 910 | 52 560 |
| Investment annuity, €/a | 0 | 1506 | 1506 | 1506 | 1506 | 1506 | 1506 |
| SAIFI, 1/a | 2.06 | 1.29 | 1.20 | 1.08 | 1.08 | 1.05 | 1.02 |
| SAIDI, hr/a | 1.20 | 1.07 | 0.88 | 0.86 | 0.77 | 0.72 | 0.71 |
| MAIFI, 1/a | 16.4 | 10.3 | 9.61 | 8.62 | 8.62 | 8.44 | 8.13 |
| Outage cost benefit, €/a | 0 | 20 990 | 7 710 | 3 370 | 3 050 | 1 940 | 1 350 |
| Savings, €/a | 0 | 19 480 | 6 200 | 1 860 | 1 540 | 434 | -156 |

It can be seen from the Table 7 that step № 6 non-profitable, so it is rejected.

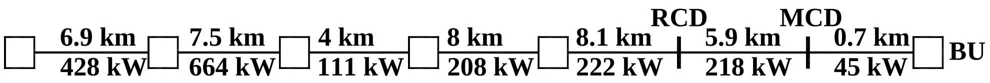



Figure 42. Feeder structure after renovation

Total costs and reliability indices change during renovation is shown in Figure 43.

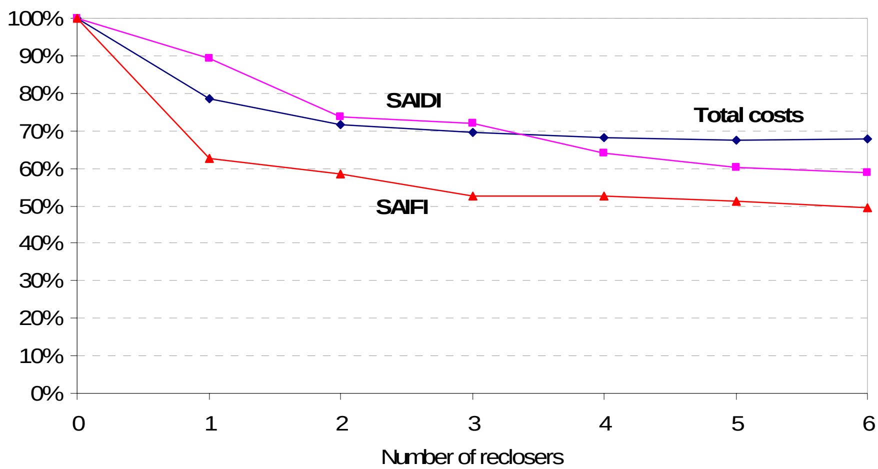



Figure 43. Results of step-by-step renovation

Profitability graph for step-by-step renovation is shown in Figure 44.

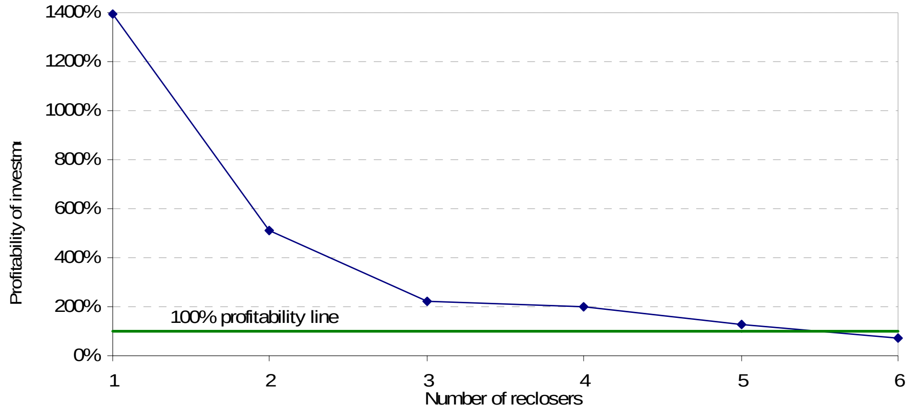



Figure 44. Profitability of investments

It can be seen from the Figure 44 that first five are feasible from economic point of view. Outage cost benefit coming from the first recloser is 14 –times higher compared the annuity of recloser investment. On the other words, first recloser repayment period is less than 2 years.

Results of the whole renovation:

| | | |
|---|---|---|
| Total outage costs: | 53 910 €/a | (reduced by 42 %) |
| SAIFI: | 1.05 faults/a | (reduced by 51 %) |
| SAIDI: | 0.72 h/a | (reduced by 41 %) |
| MAIFI: | 8.44 faults/a | (reduced by 51 %) |
| Total equipment annuity: | 7 530 €/a | (5 reclosers) |
| Total costs: | 61 440 €/a | (reduced by 34 %) |

Costs structure diagram before and after renovation is shown in Figure 45.

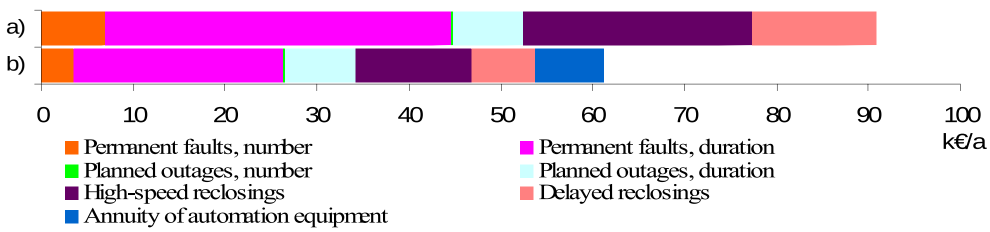



Figure 45. Costs structure a) before renovation; b) after 5th step of renovation

### 5.2.2 Single-step renovation

Single-step renovation can be done with replacement of several disconnectors at once. Amount of money which is planned to be spent on it is unknown, and there may be different reasons which make difficult to install the quantity of devices which gives the maximum benefit at once. Also, it can be planned, for example, to install 5 reclosers in 2 steps. Optimal placement of he reclosers varies depending on their quantity. Because of this, each case has to be considered separately.

*Renovation with one recloser:*

As already calculated before, the best place for single recloser is point №2.

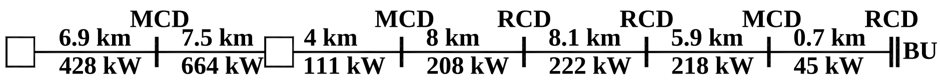



Figure 46. Feeder structure with 1 recloser installed

| | | |
|---|---|---|
| Total outage costs: | 69 980 €/a | (reduced by 23 %) |
| SAIFI: | 1.29 faults/a | (reduced by 37 %) |
| SAIDI: | 1.07 h/a | (reduced by 11 %) |
| MAIFI: | 10.3 faults/a | (reduced by 37 %) |
| Total equipment annuity: | 1 506 €/a | |
| Total costs: | 71 480 €/a | (reduced by 21 %) |

*Renovation with two reclosers:*

Optimal feeder configuration for two reclosers is presented in Figure 47.

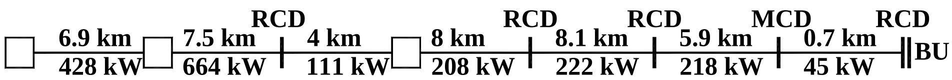



Figure 47. Feeder structure with 2 reclosers installed

| | | |
|---|---|---|
| Total outage costs: | 61 180 €/a | (reduced by 33 %) |
| SAIFI: | 1.21 faults/a | (reduced by 41 %) |
| SAIDI: | 0.85 h/a | (reduced by 29 %) |
| MAIFI: | 9.64 faults/a | (reduced by 41 %) |
| Total equipment annuity: | 3 010 €/a | |
| Total costs: | 64 190 €/a | (reduced by 29 %) |

*Renovation with three reclosers:*

Optimal feeder configuration for three reclosersis presented in Figure 48.

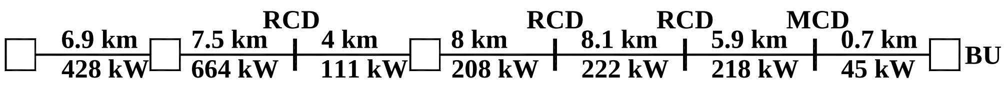



Figure 48. Feeder structure with 3 reclosers installed

| | | |
|---|---|---|
| Total outage costs: | 58 670 €/a | (reduced by 36 %) |
| SAIFI: | 1.21 faults/a | (reduced by 41 %) |
| SAIDI: | 0.77 h/a | (reduced by 36 %) |
| MAIFI: | 9.64 faults/a | (reduced by 41 %) |
| Total equipment annuity: | 4 520 €/a | |
| Total costs: | 63 190 €/a | (reduced by 31 %) |

*Renovation with four reclosers:*

Optimal feeder configuration for four reclosers is presented in Figure 49.

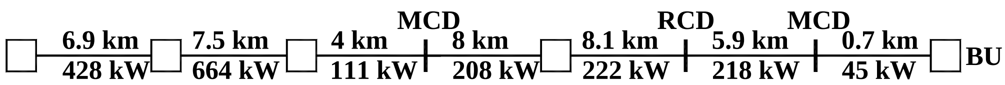



Figure 49. Feeder structure with 4 reclosers installed

| | | |
|---|---|---|
| Total outage costs: | 55 850 €/a | (reduced by 39 %) |
| SAIFI: | 1.08 faults/a | (reduced by 45 %) |
| SAIDI: | 0.77 h/a | (reduced by 39 %) |
| MAIFI: | 8.62 faults/a | (reduced by 45 %) |
| Total equipment annuity: | 6 020 €/a | |
| Total costs: | 61 870 €/a | (reduced by 32 %) |

*Renovation with five reclosers:*

Optimal feeder configuration for five reclosers and results totally coincide with results for step-by-step method, which are shown in the end of paragraph 6.2.1

### 5.2.3 Comparison of two methods

Comparison of step-by-step and single-step renovation methods is shown in Table 8.

Table 8. Comparison of step-by-step and single-step renovation methods

| Number of reclosers installed | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Total costs, €/a, step-by-step method | 71490 | 65280 | 63420 | 61870 | 61440 |
| Total costs, €/a, single step method | 71490 | 64190 | 63190 | 61870 | 61440 |
| Difference, % | 0 | 1.67 | 0.36 | 0 | 0 |

Order of reclosers' installation in these two methods differs only for 2 and 3 reclosers. As can be seen, difference between two methods is negligible and any method can be used. Distribution company can choose between these two methods depending on its needs and possibilities.

## 5.3 Results and conclusions on case network

Implementation of automated switchgear is very beneficial for the case feeder. In the result of renovation, both outage costs and reliability indices are reduced significantly. It can be highly advised to renovate the feeder using reclosers. Reliability can be improved even more, if installation of switchgear at branch lines with significant power consumption (especially, the branch line with backup connection) in the beginning of the feeder will be considered.

Feeder structure after renovation is shown in Figure 50

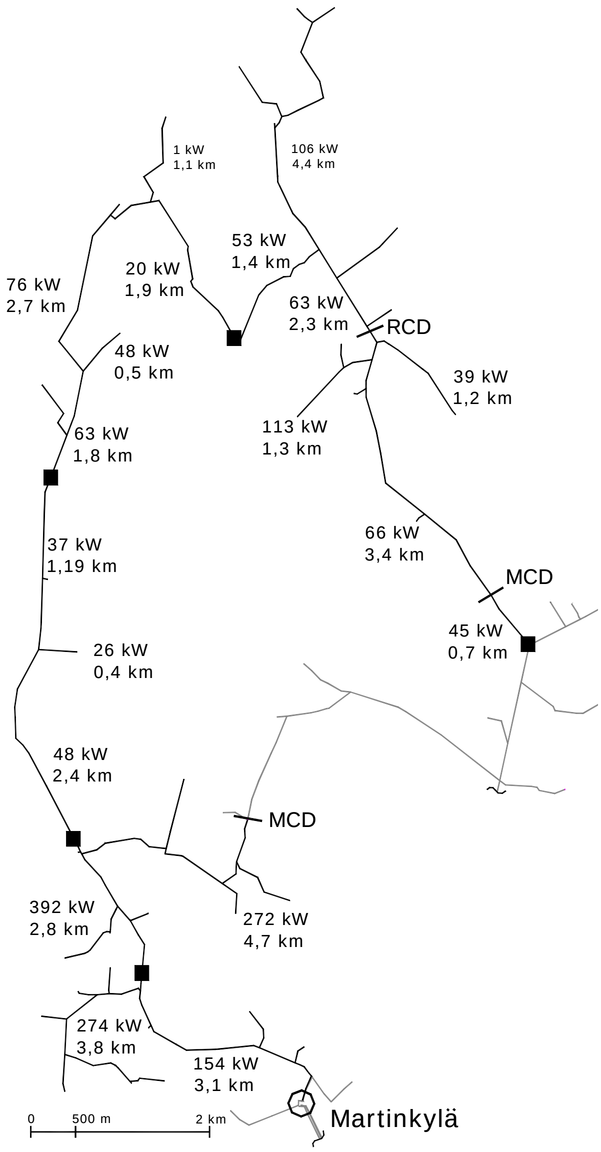



Figure 50. Feeder structure after renovation with five new reclosers.

# 6 Conclusions

Distribution business has met many challenges (ageing infrastructure, growing reliability demands, economic regulation pressure, environmental conditions), and in the close future these factors will grow further. Reliability has direct effect on distribution company rate of return. All these factors make companies pay more attention to the reliability of networks they operate

Network technology has been significantly developed during last decades (modern underground cabling technologies, network automation solutions). New network structures help to deal with reliability, and different approaches have to be combined to achieve the best results.

There are lack of reliability analysing tools and the knowledge on analysis of outage cost and effects of different kind of network investment. New tools have to be developed to supplement existing ones. In this work it is developed and presented simplified reliability tool, useful for analysis of simple feeder structures. However, it can be developed further to widen the sphere of its application and make calculations more comfortable and intuitive.

Based on results of the study it can be said that network automation has significant effect on distribution system reliability and its application is most often economically justified. It has to be noticed that results are highly depended on calculation parameters used in the study. Because of that, a lot of sensitive analysis has to be done when reliability calculations is used as a base of investment decisions.

Even the network automation can be used as an economic method to improve distribution reliability it does not substitute the need of ageing network renovation discussed in the chapter 2. This means, that at the same time when the new feeder automation is implemented into network, basic line renovation (for instance wooden pole replacement) has to be done.

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