LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Department of Electrical Engineering

Grigory Abramov

1000 V distribution system and it's potential in Russia.

Master's Thesis

Examiners: Professor Jarmo Partanen, M. Sc. Jukka Lassila

Supervisors: Professor Jarmo Partanen, professor Sergey Smolovik

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Grigory Abramov

Karankokatu 4 C 2/2

53810 Lappeenranta

Phone: +358 44 2853785

Abstract

Author: Grigory Abramov

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The application of the three voltage level 20/1/0.4 distribution system in Finland has proved to be an economic solution to enhance the reability of electricity distribution. By using 1 kV voltage level between medium and low voltage networks, the improvement in reability could be reached especially in aerial lines networks. Also considerable savings in investment and outage costs could be archieved compared to the traditional distribution system.

This master’s thesis is focused on the describing the situation in Russian distribution netwoks and consequent analyses the possibility of applying 1000 V distribution system in Russia. The goal is to investigate on the basis of Finnish experience is any possible installation targets in Russia for the new system. Compatibility with Russian safety and quality standards are also studied in this thesis.

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Grigory Abramov

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Abbreviations

CENS	Cost of Energy Not Supplied
GOST	Government Standard
EU	European Union
IDGC	Interregional Distribution Grid Companies
LV	Low Voltage
LVD	Low Voltage Directive
MV	Medium Voltage
RDGC	Regional Distribution Grid Companies
RP	Relay Protection
SS	Section Switch

Notations

$cos\varphi$	power factor
I	current [A]
U	voltage [V]
κ	discount factor
R	resistance [Ohm]
P	power [W]

1 Introduction

The same problems in electricity distribution are occurring during past years all over the world. The ageing of the networks which have been mainly built after World War II in 1950's and 1960's and growing demand for the better power quality by customers are the main prerequisites for starting found the new way of increasing the reliability. New technologies have been invented and 1000 V distribution system is among them. Finnish experience of using proved this system to be economically to improve the reliability in rural areas distribution. The main goal of this master's thesis is to determine the possible installation targets for this system in Russia and their future potential for fast growing Russian electricity market due to reform in power sector.

Chapter two is focused on describing of 1 kV distribution system. Basic building and protection principles are presented. The common components which could be applied in new technology are illustrated. Also the possible economically beneficial areas of implementation are studied in this chapter.

Finnish experience is the main content of chapter three. Problems and positive sides which appeared during real exploitation of 1000 V distribution system in Finland are discussed. Examples of real cases are provided in the end of chapter three.

Chapter four concerns the situation with rural distribution in Russia. Conditions of Russian distribution networks, components and equipment which are in use nowadays in Russia are listed in this part. In addition safety and quality regulations in Russian electricity networks depicted there.

The main aim of chapter five is to analyse the potential of 1000 V distribution system in Russia. The question of suitableness of new technology to Russian safety and quality standards is answered. The ideas of applying this system in Russia are presented.

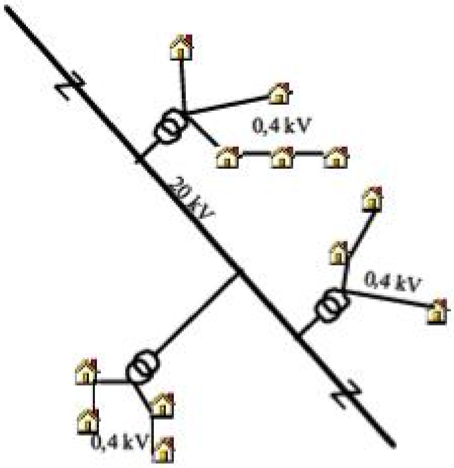
Chapter six includes the case studies of real example in Russia where 1 kV distribution system is possible to install. Comparing between traditional and new solution in various technical and economical calculations are listed.

2 Description of 1000 V distribution system

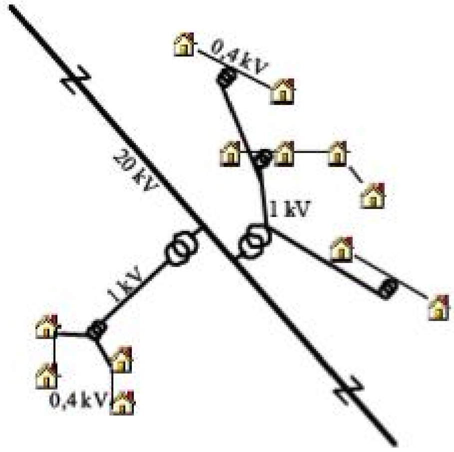
This part describes the 1000 V distribution system as a whole, their technical and economical sides. The principles of constructing and operating are explained. Components, their compatibility and possibility to use with new distribution system are analyzed. Also economical questions are represented, such as benefits of 1000 V system and where using of the three voltage distribution system can be the economically effective solution.

2.1 Explanation of 1 kV system technology

The main idea of 1000 V distribution system is to use 1 kV low voltage level between the present medium voltage (MV) network and the low voltage (LV) level. So this system acts as an intermediate between the medium voltage network (commonly 20 kV in Finland) and the 400 V network as a present type. The resulting 20/1/0.4 three voltage level distribution system has an impact on both of the systems. Consequently firstly medium voltage should be decreased to the new voltage level of 1 kV and then using distribution networks electricity delivered as near to the customers as possible. The customers cannot directly utilize the 1000 V voltage, and therefore, it has to be transformed to normal 400/230 V low voltage. The main economical range for using 1 kV line, is usually formed for low powers which need to be transmitted to a long distances. The powers which are below than 100 kW and line length ranging from a few hundred meters up to 10 km. [1] Pictures 2.1 and 2.2 are illustrates the two ways of rural electrification, traditional and by using 1 kV as an intermediate voltage level.

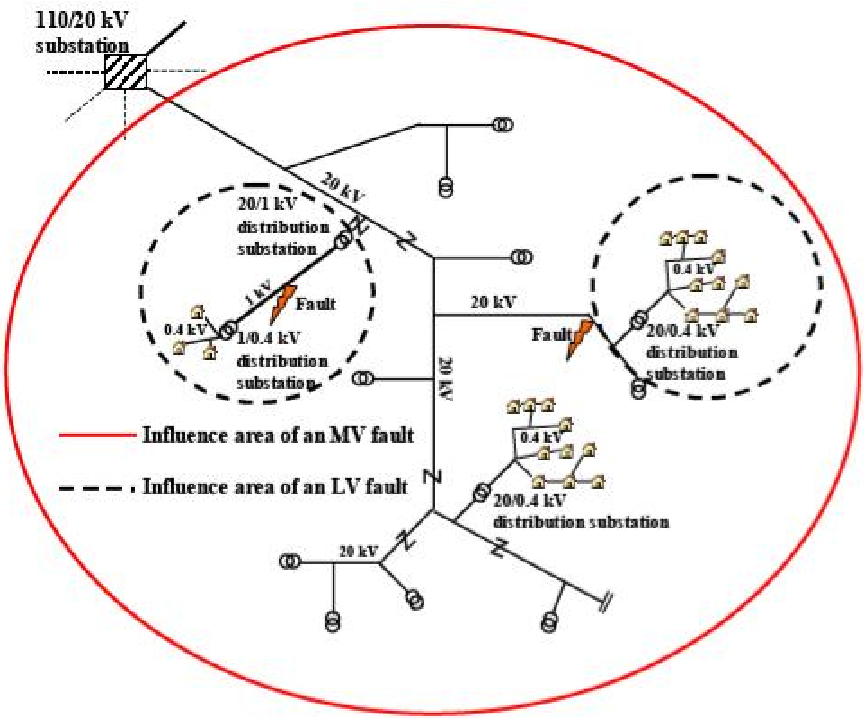


Picture 2.1 Traditional supply of a customer group [1, p.7]



Picture 2.2 Supply using three voltage level network solution [1, p.7]

Adding the third voltage level shortens the length of medium voltage network. It diminishes the number of short branches and affects the outage costs of the entire distribution network. [2] Also 1 kV system forms own protection area which have no influence on medium voltage feeders. Picture 2.3 shows the influence of the faults subject to the place of where fault occurs, in medium or in low voltage line.



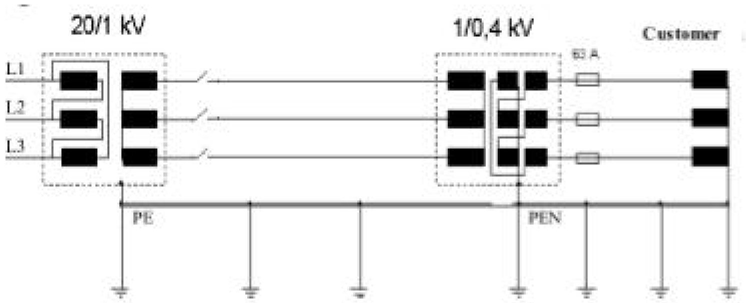
Picture 2.3 Influence area of the fault in the medium voltage line and in the low voltage line [2]

After low voltage limit growth up to 1kV, the 1000 V system became not only technically but also economically reliable, due to cost of low voltage components which are much more cheaper in designing and production because they have less requirements as medium voltage ones. In general, in 1 kV system, both the investment and maintenance cost are lower than in traditional medium voltage aerial line technology. Additionally when compared to 400 V lines, a better power transmission capacity can be reached with a 1000 V system. Since transmission capacity has linear dependence on voltage level.

Another implementation of the 1 kV systems is to transform 400 V to higher voltage level of 1 kV and then close to consumption back to 400 V. When such kind of solution applied, the economically profitability needs to be ensured. The amount of 400 V network between the medium voltage network and the 1000 V network diminishes the power transmission capacity and the voltage elasticity of entire system. Problems in feeding sufficient short circuit current may also occur in such kind of solution. [1, p.8]

2.2 Protection principle

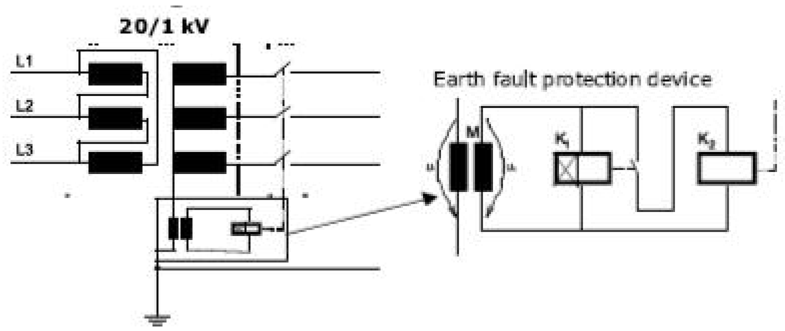
The three voltage level distribution network does not change factors which affects on medium voltage network protection. Based on measurement results and theoretical fault analyses, the 1000 V network is operated as unearthed or in other words – earth isolated. In common Finnish grounding circumstances earthing the 1 kV network can lead to dangerously high grounding voltage during an earth fault. Specifically a 1000 V network has been found to be a safety risk in double fault situations, in which break of the neutral occurs together with an earth fault. The touch voltages of the whole low voltage network in such incident exceed the allowed values essentially. If isolated neutral is used such problems does not occur. [3] Picture 2.4 presents the principle of operating the 1 kV network.



Picture 2.4 Structure of an isolated neutral 1000 V system [3]

Simple fuse protection cannot be used due to single-phase short-circuit can turned into an earth fault. And in this kind of fault situations currents are so low that fuse protection does not function. In addition fuse protection restrict the length of 1 kV line. Therefore, the protection is arranged by using a circuit breaker, which, as well as a short-circuit protection, may have a release of earth fault protection, based on the measurements of the potential between the neutral point and earth of the system. High precision requirements are set for earth fault protection to avoid error tripping. The advantage of this 1000 V earth fault protection is that the direction of the earth fault current does not have to be taken into account. Only in cases when more than one 1 kV feeders exist and protection for each needs to be set individually directional earth fault protection has to be constructed. [1, p.10]

If earth fault occurs due to increasing asymmetry of the network the neutral voltage rises. In the worst case, when the resistance to ground is near zero, the neutral voltage rises to the level of the neutral voltage. The less ground resistance will be the higher will raise the neutral voltage. The maximum, which is equal to phase voltage, can be reached when ground resistance is zero. The operation principle of earth fault protection, which is based on measuring the neutral voltage is shown on the picture 2.5



Picture 2.5 Earth fault protection of 1000 V distribution system [3]

The measuring algorithm is quite simple: the second winding of voltage transformer which indicated M on picture 2.5, measuring the neutral point voltage is connected via a time-delay relay (K1) to a trip relay (K2) which operates the circuit breakers. Normal asymmetry does not lead to tripping; trip relay is set so that only voltage in the neutral which are higher than half of a phase voltage cause tripping. [1, p.11]

The new 1 kV distribution system does not change the earthing principle of 400 V networks, so the protection principle of 400 V network do not need to be changed too.

2.3 Components

As 1 kV system is new technology it needs the development of new network components, which was not used before. Several devices such as for example transformers and protection components need to be designed from a starting point or based on technology of the exiting network components. Other components, including overhead and aerial bundled cables can be applied to 1 kV networks without any permissions “as is” because they already designed to use on low voltage, which according to the LVD (Low Voltage Directive), already classified far a 1000 V low voltage. [1, p.11]

2.3.1 Aerial lines

The overhead lines are most common solution in rural areas, almost all low voltage networks are made using aerial bundled cables in contrast to medium voltage in which bare overhead lines are commonly used. The bare overhead line are more economical but on the other hand using the XLPE-covered conductor which also called PAS conductor can reduce the number of failures of the line. In both cases when compared 1 kV system with medium voltage networks, the first one is always cost-effective solution in construction because in 1000 V system components and technologies of low voltage networks is used.

There are no differences in installation between 400 V and 1000 V wires. All components which has been using in 400 V overhead lines construction can also be used in 1 kV systems without any restriction and special requirements. The same impregnated wooden poles with same aerial bundled cables which are the most common solution for low voltage networks are suitable. So terminals, suspension-clamps and other accessories are also applicable in this new technology.

There are a lot of cables that can be applied both in 0.4 kV and in 1 kV networks. The most common aerial bundled cable is AMKA structure cables. On account of low loads in cases where 1 kV systems is being applied the most typical are AMKA 35, AMKA 70 and their multiples. A lot of advantages of this cables such as resistance for the external mechanical stresses and possibility to use more narrow line path compared to bare overhead lines, made them so widespread in rural electrification. Different types of cables, with different cross-section of phase and neutral wires and their technical characteristics are shown in Appendix A.

For a safety reasons line labelling of 1000 V lines is using. The identification can help to avoid confusion, when, for example, cables and accessories of both low voltage systems, 400 and 1000 V are mounted on the same pole.

2.3.2 Underground cables

As well as in aerial lines the 1 kV system do not take an effect on the installation method of underground cables. The same principles and cost levels as for low voltage cable trenching are existing, which a notably lower than in medium voltage cabling. So using the 1 kV systems instead of medium voltage lines can significantly increase the cabling rate in rural areas and consequently increase the reliability of distribution due to decreasing the number of faults caused by trees and animals.

At voltages up to 1000 V, the primary function of cable termination is protect and seal the branching point; in dry indoor conditions, the cable can be terminated without a separate cable termination as the electric stress does not require the use of termination , in contrast to medium voltage lines where termination and joints have appreciable influence on resulting cost. In low voltage systems a simple heat-shrink plastic termination can be used. [1, p.19]

Also in low voltage cable installation excavation of trench for cable can be replaced with ploughing which is more cost-effective solution due to less labour costs. The process of 1000 V cable ploughing is shown on picture 2.6

Picture 2.6 The process of ploughing the 1 kV cable [Photo by Pasi Kaskinen, Source: 5]

The most widely used underground cable is AXMK (explain abbreviation) cable, its technical parameters and also parameters of other cables that can be used under 1 kV voltage level are listed in Appendix A.

2.3.3 20/1 kV and 10/1 kV distribution transformers

Adding the new voltage level to the distribution network increase the number of transformers and consequently the total cost of this network. The new type of transformers is needed. Firstly to decrease voltage level from medium voltage distribution level to 1000 V low voltage level in other words 20/1 kV and 10/1 kV transformers. This transformers are constructed on the basis of the exiting 20/0.4 kV and 10/0.4 distribution transformers. The general insulation level of a transformer is determined by the voltage used in the high side of the transformer (i.e. 20 kV). Therefore, no changes have to be made to the general insulation structures of the transformer, when the voltage of secondary winding raised from 400 V to 1000 V. To avoid adjustments to the core structure, the transferred power levels should be the same as in 20/0.4 kV basis transformers. The only distinction is in the numbers of turns in the windings. As a consequence the resulting transformer have the same dimensions as

20/0.4 kV transformer and can be easily installed on the same pole-mounted distribution substations. [1, p.21]

In rural electrification there are usually a lot of unbalanced (unsymmetrical) loads, due to this a special attention needs to be paid for the vector group of the transformers. Especially, for the reason that two consequent distribution substation are applied. The advisable vector groups for these cases are Dyn and Yzn. Other vector groups may result in mismatching of phase angles and consequently cause circulating current and other system disturbances. [1, p.21; 4]

Picture 2.7 20/1 kV distribution transformer [5]

The losses level of the 20/1 kV transformer should not exceed the level of losses of 20/0.4 kV distribution transformer of the corresponding power range, which have reduced idle state losses and z_k < 4%. [1, p.21] Lists of the technical parameters and cost of the 20/1 kV and 10/1 kV could be found in Appendix A.

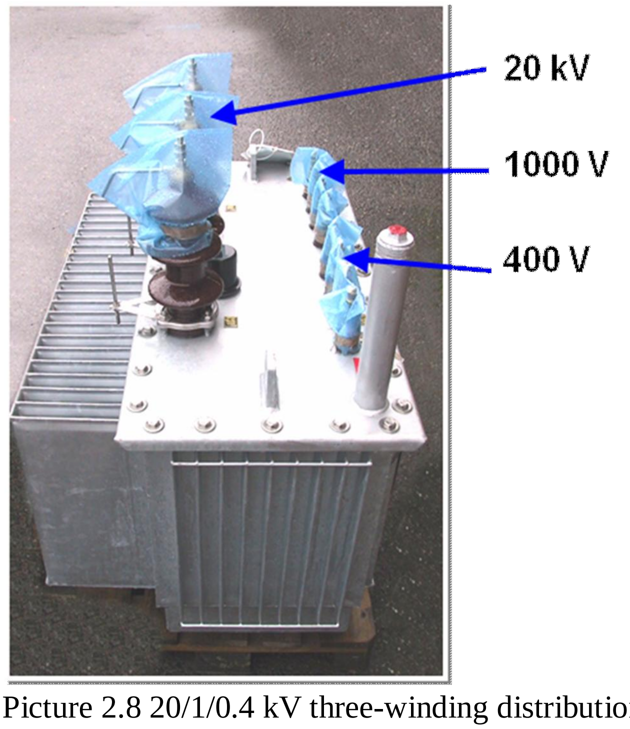
All transformers are oil-insulated, mineral or ester oil, which is more ecological. To provide the control of voltage level all transformers are equipped with off-load tap-chargers. Based on practical experience, only transformers in the range between 50 kVA and 315 kVA have market demand. [1, p.22]

2.3.4 20/1/0.4 kV distribution transformers

When there is a demand of 400 V near the distribution substation, a three winding 20/1/0.4 kV transformer can be used. Customers which are near to the substation can be supplied with traditional 400 V low voltage network, while it can also be a separate 1000 V feeder for those customers who are located further off.

Diversity of loads of three separate windings of the transformer, create a flux in the transformer core, the closure of which has to be ensured by providing a path for the flux. Therefore, this transformers are shell-type and consequently larger and heavier than two winding transformers. As a result they cannot be installed to an old pole-mounted substation. [1, p.23]

Unhopefully, there are only few transformers with not wide power range. Transformers for 50, 100 and 150 kVA powers exist. The loss levels restrictions are the same for 20/0.4 transformers, of corresponding power range. Picture 2.8 shows distribution transformer, manufactured by ELIN.



Picture 2.8 20/1/0.4 kV three-winding distribution transformer [5]

The transformer is wider than traditional 20/0.4 kV transformer and therefore it require more robust structures for pole-mounted substations, but benefits that can be achieved when using this transformers in renovation targets are more ponderable.

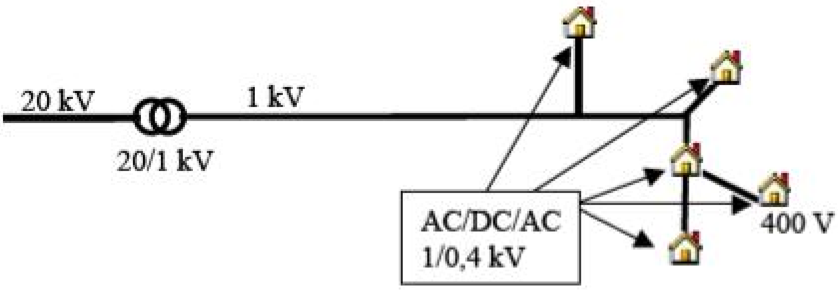
2.3.5 1/0.4 kV distribution transformers

The 1000 V distribution system requires also a second type of distribution transformer. The 1/0.4 kV transformer is needed to provide the traditional 400 V voltage level which are suitable for customers. There is no basis for the development of this transformer, so the cost of design and following production having considerable effect on the total cost of the whole three voltage distribution system. The 10/0.4 kV transformers which are firstly used as a basis for 1/0.4 transformers, are not optimal for the low voltage purpose due to the high level of insulation. Therefore, 1/0.4 kV transformers are large in size and have large physical dimensions. [1, p.23] Picture 2.9 shows the appearance of 1/0.4 distribution transformer.

Picture 2.9 1/0.4 distribution transformer [5]

Nowadays the majority of problems are solved and there are 1/0.4 kV distribution transformers on the market which meet the emerging demand of such kind of production. The technical parameters of existing 1/0.4 kV distribution transformers and their cost listed in Appendix A.

Furthermore, an idea of replacing the 1/0.4 kV transformers with frequency converters has born. Picture 2.10 shows the principle of using the frequency converter based voltage transformation at the customer’s end of 1 kV line. Additionally to small physical size and low cost of the power electronic components, there also will be any problems with voltage drop at the customer. The losses in frequency converters are almost identical to the usual transformer losses. [6]



Picture 2.10 Replacing 1/0.4 transformer at the customer end with frequency converter based transformer [6]

There are a lot of opportunities in development of 1 to 0.4 kV transformation system, only time of practical usage can prove which option is both technically and economically reliable.

2.3.6 Substation arrangements

The pole-mounted distribution substation is the most common type of substation for rural areas electrification. Lower cost compared to other substation types, such as pad-mounted or building-mounted substation makes this substation preferable. The reason is simplicity in construction and in further maintenance.

As 20/1 kV distribution transformers are similar in size and weight to the 20/0.4 transformer the same pole-mounted substation can be used. Picture 2.2 shows installation of 20/1 kV transformer on typical two-poles substation. The only differences are in protection on low voltage side, fuse protection, which are typical to 400 V network should be replaced with 1000 V protection package.

The substation for the 1/0.4 kV transformers are of single pole structure, due to less weight and dimension of this type of distribution transformers. Fuse switch protection for 400 V network is also being installed on the pole.

The economical efficiency of underground cabling using 1 kV system open market demand for the lower cost pad-mounted substations for 1/0.4 distribution transformers. This and also substation for 20/1/0.4 kV three-winding transformers needs to be designed to provide more economically effective using of three voltage distribution system.

2.3.7 Protection devices

The protection of 1000 V network is implemented with overcurrent relays and circuit breakers. The measurement of voltage between the 20/1 kV transformer and the earth of the system is the principle that is used in earth fault protection. This the most simple and cost effective method due to only single voltage transformer between the neutral point and earth suffices. The most serious risk in such kind of earth fault measurements can occur when erroneous connection during an installation existed and 20/1 kV neutral point is earthed by accident. Consequently the voltage over transformer does not occur and protection is not started. So the serious attention has to be paid to the process of installation, for that reason special training of personal is needed.

Possible alternatives for neutral voltage measurement of earth fault protection can be protection based on the measurement of insulation resistance; protection based on the measurement of earth fault current; protection based on the measurement of open triangle voltages. [1, p.27] In spite of all disadvantages measuring the neutral point voltage system has proven reliable. Picture 2.11 shows the protection package developed by ABB in coordination with Suur Savon Sähkö Oy (SSS Oy). It consists of circuit breaker with overcurrent protection, delay relay and neutral point transformer. This package usually installs on the pole near the 20/1 kV transformer.

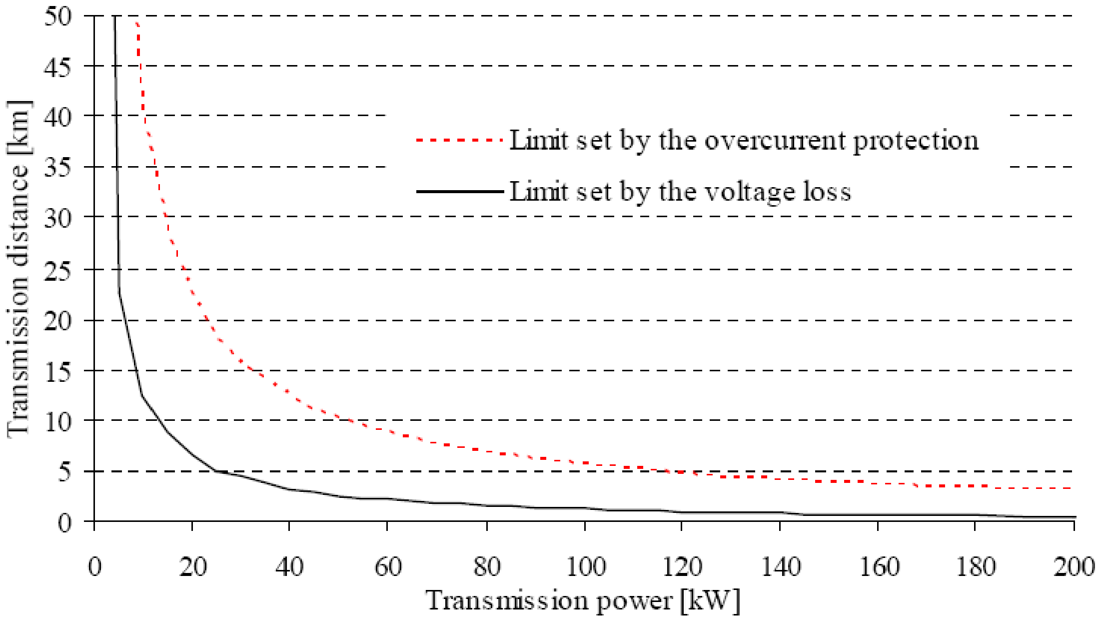
Picture 2.11 1000 V protection package

The protection of the 400 V system can still be implemented by fuses. On pole-mounted substations same pole fuse switches can be used and in case of underground cable networks fuse-switch disconnectors as before can be applied. [1, p 28]

2.4 Technical constraints

Theoretically, when voltage rises up to 1000 V, it is possible to transmit 2.5 times higher power to the 2.5 times longer distance than with traditional 400 V system, if types of the conductors are the same, but in practice technical constraints are existed. The typical technical boundaries for 1 kV distribution networks are the voltage drop of the system and thermal limit for the components. Both of these factors have an influence on the transmission capacity of the system. The combined voltage drop of the conductors and transformers defines the upper limit for the economical range of 1 kV system usage.

The range of use is also affected by the selected protection. So when using traditional fuse protection or overcurrent relay protection, the transmission distance as a function of power should be analyzed. If fuse protection is used, even at relatively short transmission distances the limits of acceptable line length is a decisive factor. When the pre-set relay protection is used, the problems with distance do not appear so early. Picture 2.12 represents the limits for the transmission distance which are set by voltage loss and overcurrent protection. Empirical tests have shown that the overcurrent protection does not limit the system's transmission distance if the maximum allowed voltage loss in the system is less than 15%. [1, p.50]



Picture 2.12 Limits for the 1 kV system transmission distance [1, p.50]

Picture shows that firstly, system meets the voltage loss limit. This factor is the main in the network design and too strict boundaries for the voltage drop can accordingly lead to overdimensioning of the system.

2.5 Economical efficiency analyses

By using the techno-economic analyses the most suitable targets for applying 20/1/0.4 kV three voltage distribution system could be found. The techniques of analyses process are constantly developing. The permanent update of techno-economic calculation is vitally important as new application for the 1000 V system could be found.

The economical efficiency analyses consist of two phases. The first is to compare medium voltage line (20 kV in case of Finland) with low voltage 1 kV line. Secondly, is to determine the economical efficiency of 20/1/0.4 kV the three voltage level distribution system compared to traditional 20/0.4 kV system. Next, the design of entire transforming districts is investigated, and then the comparison between two systems should be done. [7]

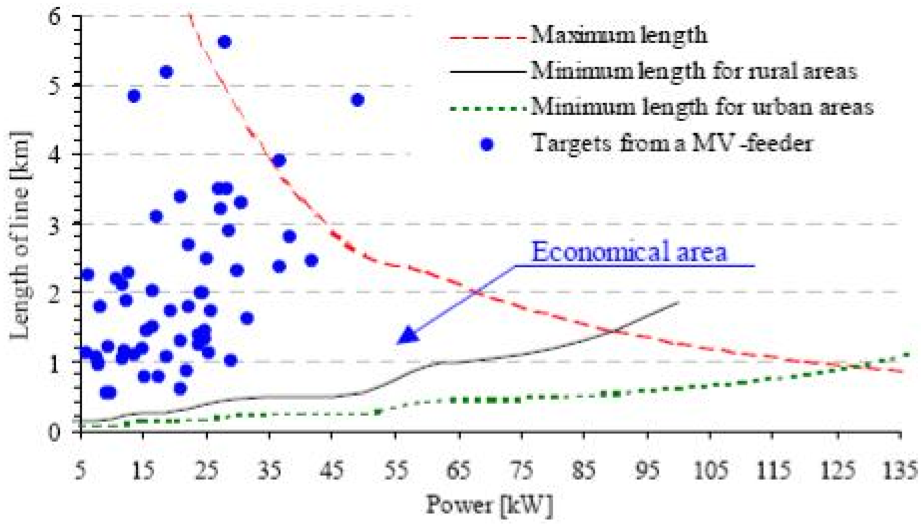
The comparison of individual lines can be divided into four cases, including replacing medium voltage lines by 1 kV lines in new construction projects; replacing a medium voltage branch line in renovation by 1 kV line; using 1 kV lines in the renewal of an exiting medium voltage network; taking the exiting medium voltage line into 1 kV use. [1, p.35]

In the calculations the unit costs presented in Finnish national cost list of network components are used, they could be found in Appendixes A. The values of the outages are estimated of the costs caused by outages to the customers. Table 2.1 represents other parameters which are used in technical and economical analyses.

Table 2.1 Used calculation parameters

Parameter	**Value**
Lifetime [a]	40
Time of load growth [a]	40
Peak operating time losses [h]	1000
Interest rate [%/a]	5
Power factor	0.95
Annual growth of consumption [%/a]	1
Price of power losses [€/kW]	30
Price of energy losses [€/kWh]	0.03
Fault repair costs [€/fault]	1640
Maintenance cost in MV network [€/km,a]	95
Maintenance cost in LV network [€/km,a]	48

With the help of techno-economical analyses it is possible to calculate the minimal economical line length of 1 kV line. In other words, to determine the interval, where applying the 1000 V system would be beneficial. As an example economical range for applying 1 kV aerial brunched cable as a replacement for 20 kV medium voltage line is shown on the picture 2.13



Picture 2.13 Economical range of use of a 1 kV aerial brunched cable compared to 20 kV medium voltage overhead line [6]

The upper boundary is technical limit, existing due to combined voltage drop in the 1 kV conductor and in 1/0.4 kV transformers which is equal to 8%. The lower limits are minimal economical line length; this is a function of used components, costs and power. The picture shows that for rural areas replacing 20 kV MV lines with 1 kV lines is economically reasonable with loads less than 85 kW and line length of few kilometres. There are no remarkable difference between 1 kV aerial brunched line and 1 kV underground cable, and their economical areas of usage are practically equal.

2.5.1 Replace 20 kV lines by 1 kV lines in new and renovation targets

There are several targets of 1000 V line implementation which was empirically and theoretically proved to have large economic potential. In new construction three main groups can be picked out. All of them are mentioned below.

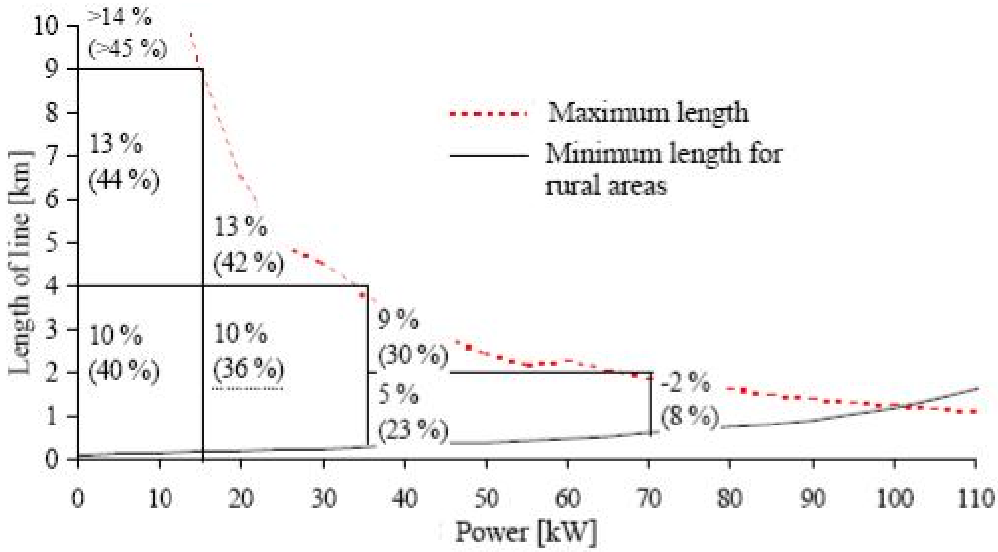
The typical solution which provide savings both in investment costs and reduces the outages cost of medium voltage network is to replace low load medium voltage branch line with 1 kV line.

In the case when there are two groups of customers in distribution area, one near the medium voltage line and another is far situated and have low load. In this target three winding 20/1/0.4 kV transformer is needed. By using 400 V feeders, customers near substation can be supplied and 1 kV line provides electricity for remote situated consumers. In this case investment cost of 1 kV line play major role, due to customers needs to pay for electrification by them and medium voltage line is very expensive alternative.

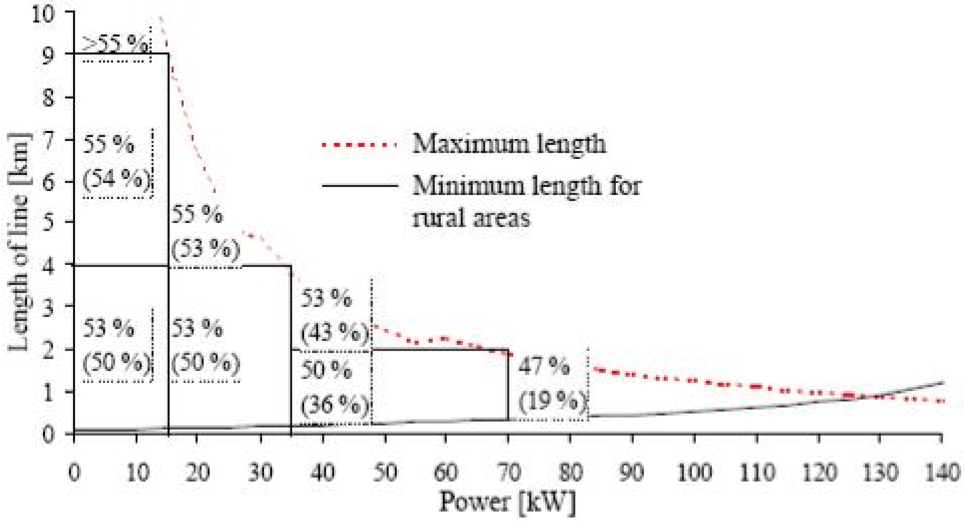
The third target is to divide large transforming districts into separate ones, so fault in one would not affect neighbour district. Nevertheless, the profitableness of 1 kV system in such case depends on the costs of splitting up the transforming districts of the traditional system. [1, pp. 36-37]

In total renovation of 20 kV MV branch line economical application areas are the same as in new construction targets. If renovation is partial, economical range decreases and mainly achieved due to savings in outage costs. The planning in these cases should be very careful.

The amount of savings depends on transmission capacity and distance. Losses that are increased due to lowering the voltage can be compensated by achievement in investment, outage, maintenance, and fault repair costs. The average savings in investment costs when using the 1 kV aerial brunched cables instead of 20 kV overhead line is 15-20%. When comparing 1 kV underground cable with medium voltage underground cable the cost difference could be up to 50-55%, this cases are showed on picture 2.9 and picture 2.14 In parentheses total possible saving are shown.



Picture 2.14 Cost difference in random sections of the economical range of application of 1 kV aerial brunched cable and 20 kV overhead line [6]

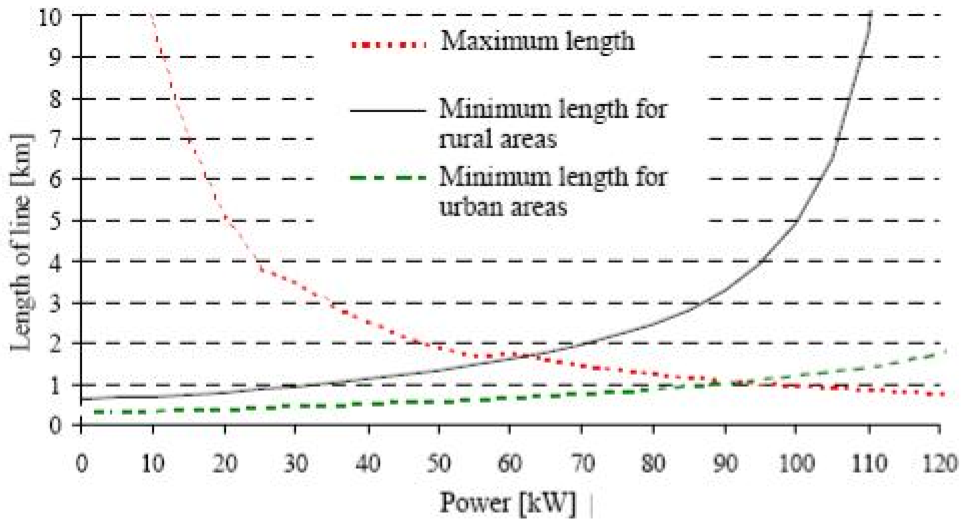


Picture 2.15 Cost difference in random sections of the economical range of application of 1 kV underground cable and 20 kV underground cable [6]

This examples show the economical potential of 1 kV system. There are a lot of possible targets to install this new technology, but economical efficiency considerably depends on interruption costs, the lower they are the less would be the area of 1 kV lines usage.

2.5.2 Another installation targets of 1 kV system

There also few possibilities to apply 1 kV system, for example, it is possible to use technically old 20 kV line on 1 kV voltage. The only investments that are needed in this case are cost of transformers and protection devices of 1 kV system. All savings that can be achieved are provided by outages, compared in situation when nothing is done. Picture 2.16 represents the economical range of such kind of usage.



Picture 2.16 Economical range of application MV overhead line on 1 kV line compared to operating on 20 kV voltage [6]

Using of 1000 V system as a replacement for 400 V line could also be effective. So a 6.25 times higher power can be transmitted using 1 kV voltage compare to 400 V if conductors are equal. This provides possibility of using the conductors with smaller cross-section.

In special conditions, a 1000 V line can be used as an extension of a 400 V low voltage network so that the distribution voltage is firstly transformed from 400 V to 1 kV and than close to consumption area back to 400 V. This option is only can be used on very low transmission powers. [1, p. 43]

In both cases cost of distribution substations shall not exceed the saving achieved in the investment and loss cost of the conductors. And, of course, they are not so profitable as replacing 20 kV branch lines.

3 Finnish experience

This chapter is emphasized on describing the Finnish experience of using 20/1/0.4 kV three voltage distribution system. The reason for start applying the 1 kV lines is explained. Also the advantage and disadvantages that are appeared in practical usage are listed.

3.1 Prerequisites for using 1 kV system in Finland

First installations and experiments in raising the voltage level of low voltage network took place in Norway and Italy in 1960’s, but due to Finnish standards and authorities was forbidden in Finland, in spite of their economical benefits. [xx] After Finland joins the EU (European Union) the situation has changed completely. Finnish standards became harmonized with EU-legislation. The LVD 72/23/EEC (Low Voltage Directive), which was applied, defines all voltages between 50 and 1000 V AC and between 75 to 1500 V DC as low voltage. [5] At the same time opening the electricity markets in Finland became reason for better electricity distribution demand. So, to improve the quality of customer’s supply the new kinds of networks solutions are needed.

The reliability of supply and disturbance-free electricity distribution are the most important thing for customers after the price of electricity, which should be reasonable. Hence the number of outages which have influence on all inhabitants has to be decreased, especially nowadays when increasing windiness and amount of snow storm caused a lot of faults to medium voltage overhead lines, located mainly in forests. The 90 % of all outages in Finland comes from medium voltage networks. Moreover this faults has greater area of influence when compared to low voltage networks.

In addition Finnish lines which built up mainly in 1960’s came to their life limit. So this leads to demand for renovation. In these targets and also in new ones there is a possibility to try a new technology that can not only increase the system reliability, but also has less investment costs.

All this prerequisites lead to that in 2000 Suur Savon Sähkö Oy started to plan their first experimental installation of 1 kV system. Empirical tests and consequent practical experience shows the beneficiary of this system. Nowadays there are hundreds of districts where 20/1/0.4 kV system is in use.

3.2 Benefits

The 20/1/0.4 kV system is an economical solution to increase the reliability of electrification in rural areas. By using 1 kV voltage between present Finnish medium voltage 20 kV and 0.4 kV low voltage networks the reliability can be enhanced without significant investments. These effects are mainly due to replacement of 20 kV medium voltage overhead lines that has low load with 1 kV lines.

By using the 1 kV system the branches of the main lines can be separated to independent protection areas with the 1 kV system, and so faults on this branches do not interrupt the distribution of whole feeder. The reason is that each 1000 V system forms its own protection area, which has no influence on medium voltage network. In the case of a failure in the low voltage network, an outage is experienced only by a single transforming district or by a part of the customers in the district. [8]

A 1 kV system is implemented with low voltage lines, and therefore no wide line path is required for the lines unlike for a 20 kV overhead line, which is the most typical solution in Finnish rural areas distribution. The natural state of the forest and natural landscapes in holiday housing are preserved. Finnish authorities pay a great attention to integrity of the environment and owing to the fact that 1 kV has a lighter structure it is easier to make land-use contracts to construct a distribution line. [9]

Additionally, 1 kV system has lower investment and maintenance costs. It is very important to end customers which, for example, are obliged to pay for the electrification of their summer cottages. Therefore, in case when medium voltage can be replaced with low cost 1000 V line, it can solve the real problem of supplying customers that can not afford the expensive solution and in other situation they would stay without electricity for a long time.

If regional policy has reliability as a main aim in development, the decision to use only underground cables can be made. Identical politics take place in coast and lake regions where overhead lines or aerial brunched cables are impossible to install due to landscape characteristics. Underground or underwater cabling provides high savings in investment and outages costs.

3.3 Problems during operation

There are several problems that are appeared during planning and consequent using the 1000 V new distribution technology system. Firstly, the new voltage level requires the new equipment, 20/1 kV and 1/0.4 kV transformers. These transformers increase the investment cost and decrease the transmission rate of 1 kV system. If 20/1 kV transformers can be easily build on the 20/0.4 kV transformer basis, then 1/0.4 kV transformers is considerably harder to invent, because it is low voltage component which needs to be constructed from the “zero” point.

The planning of three voltage system also become problematic, because in the 20/1/0.4 kV system the iteration between the voltage levels is stronger than in the case of the traditional system. Also the number of design parameters increase. Constructing these kinds of networks is in contradiction with the traditional principles of network design. [7, 11]

The problem of occurrence of partial discharges on cable surfaces exists. The most problematic situations for AMKA cables take place when water drops or ice crystals occur on the conductor surfaces. Raising the operating voltage to 1000 V makes installation damages even more critical. Additionally, for underground cables which are installed in water, tree phenomenon problem is actual. So the special attention should be paid to the installation of these types of cables in specified situation. [1, pp.11-12]

The problem in software development also exists, due to additional voltage level that complicates the calculation. The 1 kV system has to be linked to network databases, in these case at least two voltage levels should be calculated simultaneously. So 20/1 kV transformers have to be modelled as an intermediary.

To sum up, new 1 kV system provides great opportunities in distribution development, but on the other hand implementation of this new technology, especially on the first stage, connected with a lot of problems.

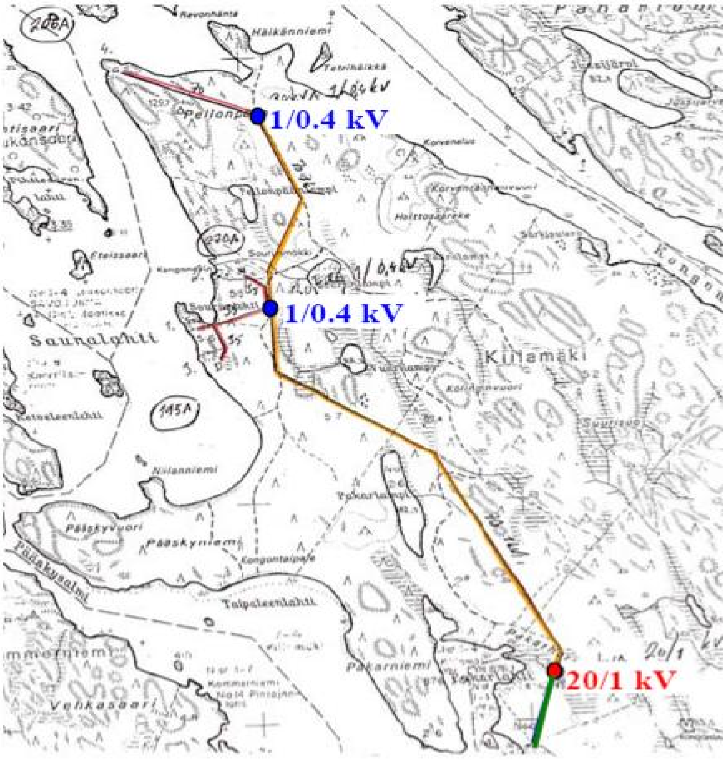
3.4 Practical experience

The pioneer in using the 1 kV distribution technology is SSS Oy. The first target was officially presented in autumn 2001. Picture 3.1 shows example's topology. This and all consequent installations have been done to avoid 20 kV medium voltage branch lines. The number of target has rapidly increased since that time. Nowadays three voltage distribution system has become a normal part of network design. Company constantly use three voltage distribution system in replacing over 40-year-old medium voltage lines with low loads in sparsely populated areas. The SSS Oy now has 93 targets in total, feeding over than 500 customers through about 300 km of 1 kV lines. [5] All lines are mainly built up with aerial brunched cables and only few targets are made with underground cables. The number of installed transformers of different types is listed in table 3.1

Table 3.1 Amount of transformers of a new types installed by SSS Oy [5]

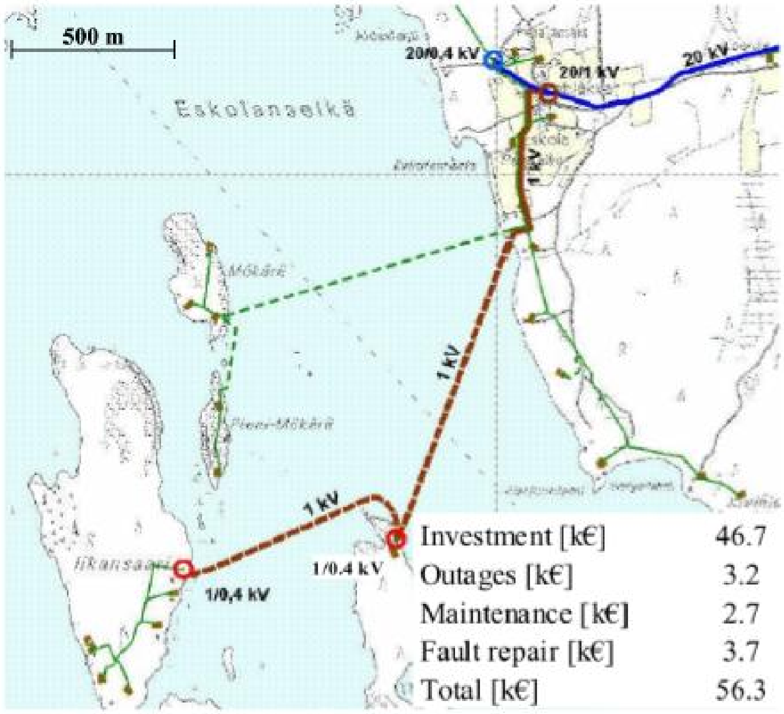
Transformer type	**Amount, kpl**
20/1 kV	50
20/1/0,4 kV	45
1/0,4 kV	122

The delicate lake environment of Kongonsaari, which is located south of Savonlinna, was chosen to be the first installation target (Picture 3.1). Newly developed components such as protection package and 1/0.4 kV transformers was applied for the first time. The feeding of three customers with total power of 16.5 kW using 20/1/0.4 kV distribution system saved 34% in total costs comparing to traditional 20/0.4 kV network, mainly due to achievement in investment and in outage costs. The forest has been saved also, because 1 KV line is environmentally friendly.



Picture 3.1 1000 V line at Kongonsaari [10]

The second target is situated on archipelago of Lake Puulavesi, eastern Finland. Seven customers which are located on islands were electrified by using 1 kV underground cables. Picture 3.2 depicts the example and also its cost is presented.



Picture 3.2 1000 V underwater cable on archipelago of Lake Puulavesi [7]

In this case the power of the island situated customers was higher than transmission capacity of 400 V cable, so only two options have been existed, one have been the using of expensive 20 kV underwater cable. In this case customers would have been without electricity, due to high investment cost. The 1 kV system provided 50% cost saving solution. Hence, 20/1/0.4 kV system has proved to be beneficial system for electrification of leisure time settlements on the coasts and islands. [7]

3.5 Future market potential

According to surveys there are on average 20% of Finnish medium voltage lines that can be replaced by 1000 V lines. As length of overhead lines in Finland is 114,100 km and one 20/0.4 kV transforming district per kilometre, [12] the potential amount of 1 kV can be estimated to be 23,000 km at maximum and the total number of 20/1 kV and 1/0.4 kV substations is 20,000-25,000. Correspondingly to this about 1000 transformers of different types will be needed annually. [1, p.45]

The SSS Oy not only one company which has 1 kV lines in use, also such distribution companies as Fortum Oy, Vatajankosken Såhkö, Porvoon Energia Oy, Parikkalan Valo Oy. In Etelä-Suomen Energia Oy, Nykarleby Kraftwerk, Merenkulkulaitos 1000 V network design are in progress. [5] Several companies in Sweden, Norway, and Italy have interest in this new technology. The feedback from Baltic countries has also been positive.

On account of that almost all over the northern Europe and also in Russia, the rural electricity distribution has the same typical characteristics, overhead lines situated mainly in forests, low loads. So it can be assumed that market potential is rather high in total.

4 Present day of Russian rural areas distribution networks

This chapter is focused on describing the situation in Russian rural areas distribution networks. The emphasis is on the technical and economical sides. First part recounts the structure of networks, principle of building and components which are in use. Economical side explains the structure of ownership shows the amount of aging networks and plans for their renovation.

4.1 Overall situation

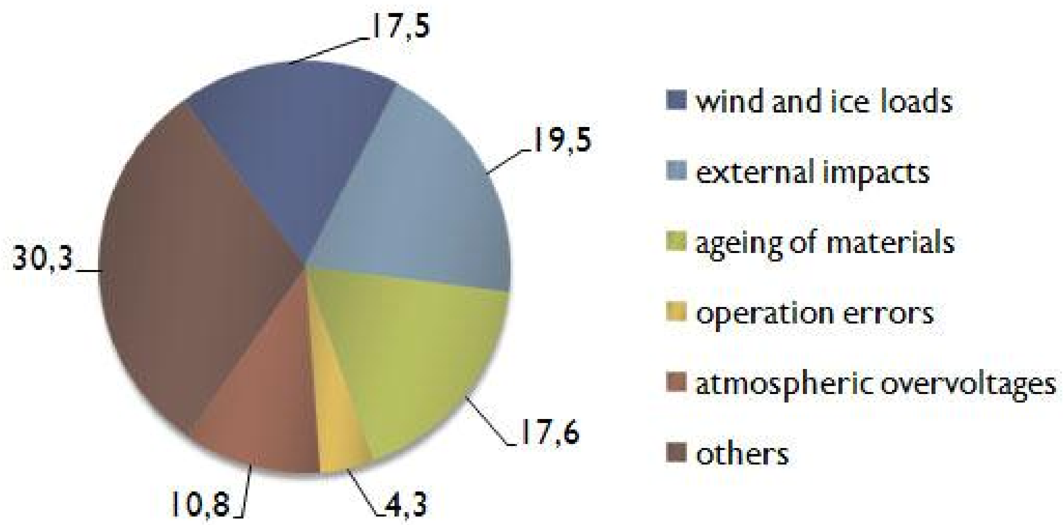
Russian electricity distribution systems in rural areas were mainly built up in 1960th when rapid growth of electricity demand required inexpensive and fast in building solution. Therefore the cheapest non-impregnated poles and wires with thin cross-sections were used. An underground cabling is very unpopular way of electricity distribution in rural areas because of its cost and complicated way of installation. The biggest part of lines built up in these years is still in use. These lines are in need of renovation in accordance with present loads. In addition increased wind and ice loads due to climatic change lead to mass and long lasting customer’s disconnections, which can last up to 70-100 hours annually. For comparison in developed countries this index is 7-10 hours annually, on one order lower. [13] More than a half of lines which is situated in rural areas are not in satisfactory conditions. State of the networks is characterized with lowering technical and economical efficiency, as for the past decade they haven't been renovated. The life time of more than 40% of aerial lines and underground cables and 30% of distribution substations is over and further operation of them is unsafe. [14] Last years numerous cases of failures even lead to disconnections of entire villages and far situated settlements, the main reasons of this are system breakdowns, customer's default of payment for electric energy and stealing wires from overhead lines. Considerable growth of losses and reduced reliability of electricity distribution affects up to $1.5 \cdot 10^9$ roubles of outage costs annually to husbandry. [15]

In addition the level of automation of rural areas distribution systems is very low. About 38 % of feeding centres equipped with remote signalization and only 16% have remote control. In relay protection mainly (98%) electromechanical relays were used, which are big in size and consume a great amount of electrical power. [16] Additional disadvantage of this relays is their low sensitivity. This type of relays have been using for the last 25 years and therefore they became obsolete.

On account of lack of financing in 1990th the rate of reconstruction, technical renovation and new building of distribution lines decreased. As a consequence attrition of network components increased up to 40% and higher and this process will continue. Besides, the average technical level of equipment installed in Russian distribution networks fit with components which were used in European countries 30 years ago.

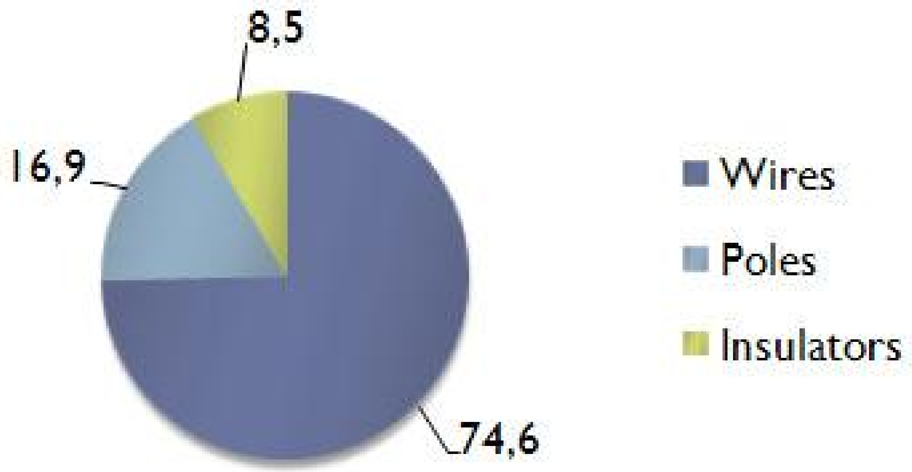
4.2 Technical side

Traditionally electric networks of 10 kV are the weakest element in system which accomplishes supplying the consumers. More than 70 % of all fault situations in Russia are coming from medium voltage 10 kV lines. Picture 4.1 shows the different causes of faults in MV lines. It is very important to know the state of medium voltage lines for better understanding the problems in distribution networks. So in future the right solution for these problems could be provided and the right way of systems development will be chosen.



Picture 4.1 Causes of faults in 6 and 10 kV networks, in percents (Source: [23])

The main causes of faults on distribution lines according to this graph are wind and ice loads, material ageing and different external impacts, such as for example tree falls on the line. Picture 4.2 depicts what elements of overhead lines are the most vulnerable.



Picture 4.2 Structure of line elements damages (Source: [23])

The components and technical solutions which are now in use in Russia would not provide needful quality and safety requirements to fit with permanent growth of consumption which are now taking place in the country.

4.2.1 Voltages

In contrast to Finnish distribution system which has traditionally been comprised of two voltage levels in their structure, the low voltage level is 380/400 V and next voltage known as medium voltage is nowadays established as 20 kV [1, p.7], Russian distribution system has traditional 0.4 kV as low voltage and 6 kV, 10 kV, 15 kV and also 20 kV medium voltage levels which are used in rural areas. So many kinds of voltage levels caused by historical development of Russian distribution systems.

The permanent growth of the electricity demand was the prerequisite for increasing the transmission capacity and consequently the rising of the voltage levels in distribution system. Started up with 6 kV which was the primary voltage level in distribution system of factories and plants and consequently this voltage was used to supply electricity for the domestic customers who were situated near the enterprises. Soon the growth of the loads made using of this voltage level technically unjustified. For that reason in 1950th it was entrusted to stop using the 6 kV and replace it with 10 kV systems, but even nowadays in old part of towns and partly in rural areas this voltage level is preserved. [17]

The 15 kV voltage level, non-typical for Russia, is used only in Kaliningrad, where it hasn't been changed since World War II because this territories belong to Germans, who traditionally used this voltage type in medium voltage distribution systems. At the present time this voltage level is not developing and insensibly forced out by 10 kV systems. [17]

As for 20 kV level, which had been used in Latvia till 1980th, it has just started to use in big cities in Russia, where loads are big and 10 kV won't secure needful transmission capacity. [17] Using this voltage level in rural areas in nearest future won't be technically and off course economically reliable.

The 35 kV voltage level which is also belong to medium voltage group, is used above this levels as intermediate voltage to bundle high-voltage with distribution voltage levels. In addition some amount of 110 kV lines can be named as distribution, as they belong to distribution companies, but this voltage level is high and don't have influence on the topic of this diploma.

Using of different voltage levels in medium voltage networks considerably increase cost of maintaining but don't rise up the reliability of electricity distribution. Unified strategy in using and development of nominal voltages in Russia is needed.

To sum up the main distribution level in Russia is 10 kV, the others are very rear and used only in individual parts of the country, thus the percent of these voltages are low. So, all the consequent dimensioning and equations will be carried out using 10 kV as distribution voltage level and 0.4 kV as low voltage level.

4.2.2 Length of lines

The territory of Russia is considerably bigger than territory of Finland, therefore the length of overhead lines and underground cables are longer. The total length of medium voltage distribution network in Finland is 124,700 km, of which 114,100 km is comprised of overhead lines. [1, p.44] Table 4.1 represents the extension of all Russian distribution lines subject to voltage level.

Table 4.1 Length of Russian distribution lines (Source: [18])

Voltage level, kV	**Overhead lines, x 1000 km**		**Cable lines, x 1000 km**
	line routes	wires	line routes
35-110	396,2	490,5	2,2
3-20	1173,2	1174,8	240,1
0,4-0,6	1186,7	1191,0	103,5
Total	**2756,1**	**2856,3**	**345,8**

In Table 4.1 the length of overhead lines offered in two different indexes, the length which is calculated by line routes and the length of wires which is permanently longer because of sags. Another conclusion that could be made from this table is small amount of cables used in Russian distribution systems, especially on high voltage levels. The sum of equipment and installation costs made cabling uneconomical solution for rural areas.

The total length of lines can be divided into two parts, according to the place of line installation: lines which are situated in rural areas and lines which belong to cities. As territories that can be named rural are considerably bigger in total size than city areas, consequently the length of rural electricity distribution lines 0.4 – 110 kV are longer and have $2.3 \cdot 10^6$ kilometres in total. [13] It's more than 70% of all Russian distribution networks. Table 4.2 lists the total amount consists of lines with different voltage levels.

Table 4.2 Length of Russian rural areas distribution networks (Source: [18])

Voltage level, kV	**Line's length, x 1000 km**
110	110
35	160
6(10)	1150
0,4	880

According to table 4.2 the 6(10) kV networks are the most lengthy and therefore has a great impact on electricity distribution reliability in rural areas. For comparison the length of city's electricity distribution lines 0.4-10 kV is $0.9 \cdot 10^6$ kilometres. [13] Both in Finland and in Russia the biggest part of the outages experienced by the customers are due to faults in medium voltage network. Moreover, the line's extensions, which are very long, complicate the maintaining of distribution networks, it usually takes a lot of time to locate the fault and afterwards to get to the fault place.

Moreover the problem of long feeders also exists. The extension of 6(10) kV lines is noticeably higher than optimal length of 8 – 12 km, so there are 13,3% of lines with length over 25 km and 2,2% of lines with length more than 50 km. In low voltage 400 V lines situation is even worth, as the distance from the distribution substation increases the cross-section of wires become thinner and also the number of phases decreases. [19]

With longer lines, however, outages affect more customers. In addition, locating faults along longer lines is difficult, and voltage drops across the length of these lines are more severe.

4.2.3 Building principles

Commonly in Russia aerial lines has been used for building medium voltage distribution networks. Cables are very expensive solution, and used only in situations when another way of supply can't be provided and also usually for safety reasons, even so they can increase electricity reliability. The large amount of cables can be found in city areas where such way of supply is rather common among all developed countries. Nevertheless when cable systems were built up, loop circuits or circuits in the form of two-beam with one or two transformers in substations were used. Generally paper insulated cables with oil dipping were used.

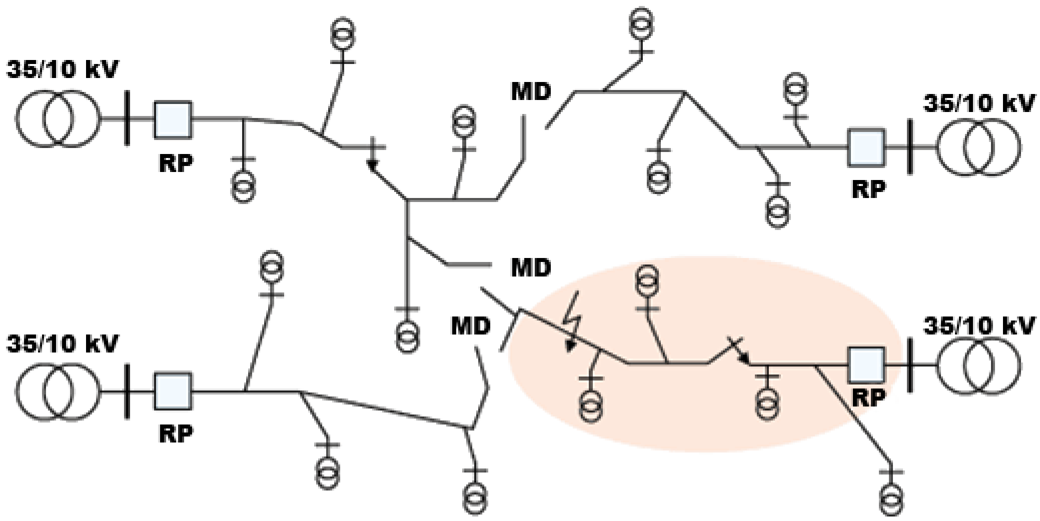
The layout of this network has been generated in 1970th, and unfortunately, not in the best way. Overhead lines were constructed with a lot of branches, and lines had a great length (up to 120 km). Poor-quality non-impregnated poles, insulators and aluminium wires with underestimated cross-sections were applied.

Afterwards, part of these networks was reconstructed using more strong components. Impregnated wooden poles and poles from reinforced concrete were started to use, wires became steel-aluminium and linear insulation stronger. As insulators porcelain and glass insulators are used. [22]

However, Soviet Union's technical standards and parameters that were accepted for this network was used as main criteria the cost of the lines, not the reliability. Medium voltage distribution networks were designed using cheapest components for life time of 5-10 years. As an example it were long spans (more than 100 meters), poles from reinforced concrete but with lowered moment of deflection (max 27 kN·m), line paths were narrower than they should be. [16] These lines are still in use and of course they don't fit present requirements of electricity reliability. Particularly when weather disasters take place, as a result mass customer's disconnection occurs.

The lowest technical level has low voltage 400\230 V overhead lines. The 62 % of them built up with wooden poles with poor quality impregnation or even without it. Wires which were made from aluminium are mechanically weak, and expose to break. The majority of line routes pass through gardens and green plantation that make difficulties in maintaining of these lines.

Aerial lines built up using radial principle with treelike structure like in Finland. The picture 4.3 illustrates the common circuit of Russian distribution networks.



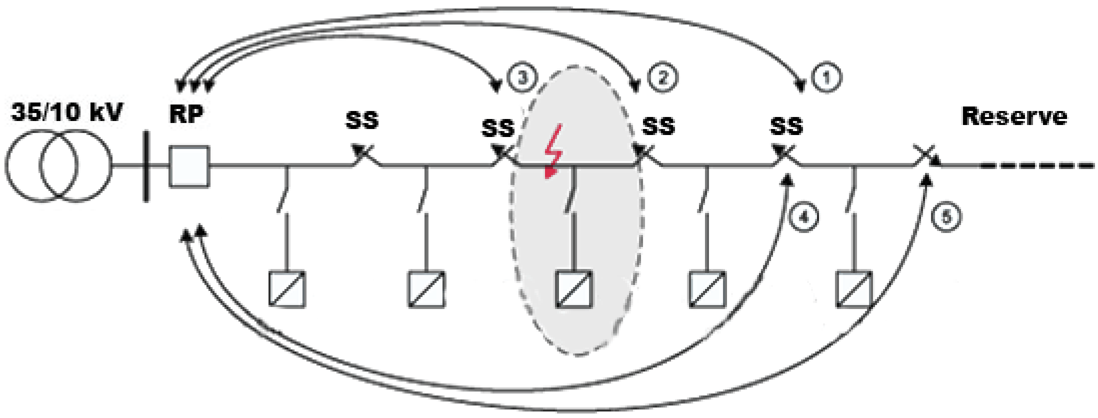
Picture 4.3 Russian distribution networks structure [20]

The cross-sections of wires decreasing stepwisely and there are a lot of backup feeders interconnected with manual disconnectors (indicated as MD on the picture). Protection equipment (RP) installed in feeding centres. Also autoreclosing equipment is installed in these points of distribution networks. The average length of main lines is about 16 km; the length of branches is 5-6 km. Also the discontinuity in loads takes place. [20] The structure of medium voltage networks showed on picture 4.3 is the best solution for rural areas, because density and importance level of loads is not so high.

4.2.4 Protection principles

Relay protection is a complex of equipment, which accomplish disconnection of damage elements and localize the fault. Protection equipment is usually installed in feeding centers, in other words on primary substations, consists of low-oil-content circuit breakers with electromechanical terminals of relay protection. The autoreclosing equipment is also situated on the feeder connection to the primary substation. Autoreclosing tries to plug line again into work after a period of time after short circuit or another fault. If fault is over, for example in case of lighting overvoltage, autoreclosing will be successful and line will continue their work. In other case whole feeder would be without electricity till time, when fault will be localized and cleared.

Fault localization is provided by dividing lines into sections, between them section switches are installed. The length of these sections is about 10 km usually. Localization and consequent connection of reserve capacity are manual and takes a lot of time and human resources. Picture 4.4 represents particular features of fault clearing in such kind of circuit.



Picture 4.4 Stages of fault clearing [20]

According to this picture five main stages can be picked out. Arrows shows the movement of field crew, firstly (stages 1-3) between sections switches (marked as SS on picture) to localize the place of fault. Then, on fourth stage, connection of sections untouched by fault is accomplished. The last fifth stage is to connect the network reserve to feed the customers. [20]

Equally in Russia and in Finland reclosers, which provide immediate clearing of the fault, are not in use. The main difference between networks is that Russian system is not as automated as Finnish. The disconnectors which serve to separate the fault location are usually manual in Russian rural areas. Taking into account length and places where line routes lie, time of manual switches can reach up to several hours or days. Therefore the reliability level of non automated network is considerably lower.

4.2.5 Relay Protection and Automation

Situation with relay protection and automation is same as in the whole Russian power industry, caused by abrupt lowering of investments since 1980th years. Even in last five years investments has been half as much of minimum needed. Consequently networks protection is in a sad state. The amount of physically depreciated relay protection equipment growth in 2% annually and mounted to 46% in 2004. At the same time this index had already been 50% in 2002 for equipment which was installed on electric power stations. The percent of erroneous tripping of protection because of ageing is rising year by year. [21] Table 4.3 shows the amount of incorrect trippings of relays by years due to their conditions.

Table 4.3 Amount of wrong tripping due to exceeded life time (Source: [21])

Year	**1998**	**2000**	**2002**	**2004**
Amount of wrong tripping caused by deterioration (%)	6,1	10,6	15,2	18

Conditions of relay protection and automation equipment even worse than situation in distribution systems as a whole, the reason is that financing of this part of systems is carried out last.

Mostly all of 6-35 kV connection equipped with discontinuous electromechanical relays and about 6% are equipped with static (semiconductor’s and microelectronic) relays. This relays has been used for more than 30 years, since 1976. Table 4.4 represents the different types of relays and their amount in Russian distribution networks.

Table 4.4 Types and amount of relays in Russian distribution networks (Source: [21])

Type of relay	**Number of relays (× 10^6)**
Electromechanical relays	
Current relays, series RT-40, RT-140	3,2
Voltage relays, series RN-50, RN-150	1,06
Current relays, series RT-40, RT-140	1,05
Time relays, series RV-100, RV-200	2,95
Interposing relays	19,0
Indicating relays	2,0
Static relays	
Current, voltage, power directional, reclosing relays	1,9
Total amount:	**31,16**

Using old-fashioned electromechanical relays can't guarantee neither stability of relay parameters during life time, nor lower the calibration and exploitation expenses and provide the needed level of network automation. The cost of new microprocessor-based relays with a lot of features most of which won't be needed in the near future is very high and made them economically ineffective alternative. Solving of protection problem can be fulfilled by using Finnish experience, where during 1980th all electromechanical and static relays was replaced with simple current microprocessor's protections. Consequently, the level of automation increased and quantity of staff in distribution companies per 100 kilometres of lines are 10 times lower than in Russia.

4.2.6 Substations

There are three types of primary substations, due to voltage types existed in Russian rural areas distribution networks. The main part consist of 35/10 kV substations, usually equipped with one transformer with nominal power 1000 – 6300 kVA and tap-changer on the high voltage side. Sometimes there are two transformers on such kind of substation, but in rural areas this is rather rare situation. Secondly, 110/10 kV substations are in use, they consist of two transformers with nominal power from 2500 kVA to 40 MVA with on-load tap-changers. About 67 % from the whole amount of primary substations had been built up till 1980 and their life time limit has already been over. Equipment used in substations, such for example disconnectors are archaic, and therefore the level of reliability is rather low. [22]

Typical rural area distribution substations usually called one-ended, single-ended or also terminal substation. These substations replenished with only one transformer in substation. In rural distribution networks there are about 513500 of 6/0.4 kV and 10/0.4 kV substations with total load of 111 GVA. Typically these substations are pole mounted or package type. The allotment of other substations types are only 10 % of total amount. For safety reasons distribution substations are frequently surrounded by fence. [18, 22]

After crisis in 1990's the consumption in rural areas decreased as well as everywhere in Russia, but for the last five years it has been raising on about 1 % annually. One of the reasons is development of the private farming. As predicted, volume of the consumption will reach the level of 1990 by 2010 year. The technical level of transformers would not provide the needed level of distribution. On the other hand situations with load levels are different along territories of Russia, so in sparsely populated areas there are a lot of low-loaded substations, with transformers, which are loaded only on 20-40% of their nominal power. Cost-effective rehabilitation of the aging, lightly loaded substation equipment was among the primary goals nowadays. New utilities should serve rural loads reliably and with quality voltage regulation.

4.3 Safety Regulations

The main document in Russia that provides regulations for electricity devices and networks designing, exploitation and maintaining is "Rules for electric equipment exploitation". [24] Also safety requirements are widely described in this paper. "Rules for electric equipment exploitation" is an official document, and therefore all rules and regulations are compulsory and must be applied permanently, starting from network design process for all organizations, private and government.

According to [24] all networks with voltage level higher than 1 kV should be maintained with isolated neutral or with effectively earthed neutral. It means that arc suppressions coil or resistance needs to be used between neutral point of network and ground. In 6 – 35 kV electricity distribution networks which belong to RAO UES the principle of neutral connection depends on the value of capacitive currents. If currents are low, then network will be neutral isolated. If currents exceed some nominal value, then neutral earthed through the arc suppression coil will be used.

In isolated neutral system, one phase fault would not cause the line emergency disconnection, because earth fault current is low due to deficiency of conductive contour between neutral of the system and ground. Consequently customer's electricity supplying would not be interrupted.

Safety and equipment damage aspects of single phase-to-ground faults were of concern. Russian regulations limit ground-fault current to no greater than 10 A. With such a low current, industry regulations do not require the circuit to be disconnected immediately but can wait several hours. The fault can present a touch potential hazard to humans and animals during that time. In addition, ground-fault currents also have been found to result in the deterioration of the concrete poles, leading to eventual pole failure. As a result, faulted poles are usually replaced following a ground fault. [25]

Ground faults also cause high sustained 50-Hz voltages (greater than 173% of the line-to-ground nominal voltage rating) on the healthy phases. The high voltage can lead to cable, potential transformer and other equipment failures. Additionally single-phase fault can lead to fault between phases. Therefore, in spite of allowance for network working with earth fault, there is a recommendation to find and clear the as early as possible, but single-line ground faults are tough to locate. The low-magnitude current causes minimal damage that is difficult for patrolling linemen to observe. Because current flows everywhere in the system and on all three phases simultaneously during the fault, identifying the faulted feeder proves challenging.

As for the networks with voltage level less or equal to 1 kV both isolated and earthed neutral are applicable. The most typical is four wire systems which are in use in 380 V networks in Russia. In these networks neutral and neutral wire must be earthed. The reason is that insulation control between neutral wire and ground is impossible. Neutral wire that has insulation defects has high fire risk, because during the single-phase earth fault current can flow through neutral wire. If cross-section of this wire is not wide enough, then it will cause conductor heating and as a result possible inflammation.

In case of three wire system, where neutral is earthed and consequently neutral wire is optional in such kind of networks. Hence, the voltage level is lower than in medium voltage networks, single-phase fault would not cause arc and therefore arc suppression coil is needless. However, capacitive currents could cause risk for personnel if touch with healthy phase happened. Safety magnitudes of currents could only be existed in networks where quality of insulation is good and amount of branches are not very high. Both neutral options can be used in low voltage networks; in low branched network it is better to use isolated neutral system, in other conditions earthed neutral is preferred.

Usually to provide safety in the case when people or animals touch external parts of electrical equipment during the fault caused by insulation defect automatic disconnection protection is using. Table 4.5 lists the time during which fault should be cleared in low voltage networks where neutral is earthed.

Table 4.5 Maximum allowed time of automatic safety disconnection in earthed system. (Source: [24])

Nominal phase voltage, V	Clearing time, s
127	0.8
220	0.4
380	0.2
more than 380	0.1

If network is neutral isolated, protection should work when two phases are connected to the parts of equipment which could be touched by people or animals. Table 4.6 shows the maximum allowed clearing time for this case.

Table 4.6 Maximum allowed time of automatic safety disconnection in isolated system (Source: [24])

Nominal line voltage, V	Clearing time, s
220	0.8
380	0.4
660	0.2
more than 660	0.1

The safety is one of the main questions in low voltage networks, because they are the link to the customers and situated near them. So, possible injuries could occur if needful level of safety would not be provided. Therefore the safety regulations must be carried out properly.

4.4 Quality requirements

Quality of electric energy is defined in government standard GOST 13109-97 [26], all characteristics which have dependence on voltage quality are defined there. There are several values which are standardized. One of the main index whose changing is most noticeble for end users is voltage deviation. Voltage deviation has a strong influence on technico-economicall parameters of all elements in the network. There are two possible values, normal allowable value and maximum allowable value. The normal allowable value of voltage deviation a equal to ±5 % of nominal voltage. This interval should be kept during 95 % of working time, the rest of the time maximum deviation value is permissable. The maximum allowable interval of voltage deviation is equal to ±10 % and could be calculated using equation 4.1

$$\delta U_{st} = \frac{U_{st} - U_{nom}}{U_{nom}} \cdot 100 \qquad (4.1)$$

Where U_{st} is steady-state value and U_{nom} is nominal phase voltage, for the customer's low voltage networks the nominal voltage in Russia is equal to 380 V. In some cases the lower allowed voltage is defined in contract between customer and energy supply organization. Typical voltage drop in these cases for rural areas is 7.5 % from nominal phase voltage, which is equal to 380 V according to GOST 21128-83 "Rated voltages up to 1000 V". [27]

Also the frequency deviation is rated in GOST 13109-97, the normal permissible interval for frequency is ±0.2 Hz and maximum allowable deviation is ±0.4 Hz. Furthermore, flicker doze is rated in this regulation standard, which determines the visual perception of luminous flux fluctuation. Additionally, several values like harmonicity of the voltage, asymmetry of voltage, allowable time limit for possible voltage sags and impulses are defined.

4.5 Reliability requirements

Reliability requirements depend on the customer's type and amount of its consumption. In Russia all end-users are divided into three categories. The first category consist of electricity consumers, outages in supplying which could lead to risk for the people, significant economical losses, damages of high-priced equipment, stop of complicated technical process, mass spoilage of production. Consumers of this category are for example water pumps of fire stations, ventilation systems on chemical factories, radio and television equipment, elevator's supply. Permissible interval in electricity supply for first category customers is equal to 1 minute. From first category, special zero-category can be separated, to which vitally important electrical equipment belongs, e.g. utilities in operating rooms in hospitals, emergency lighting. Supplying of first category customers should be provided from two independent electricity producers with automatic switching between them. For zero-category additional third power supply is needed.

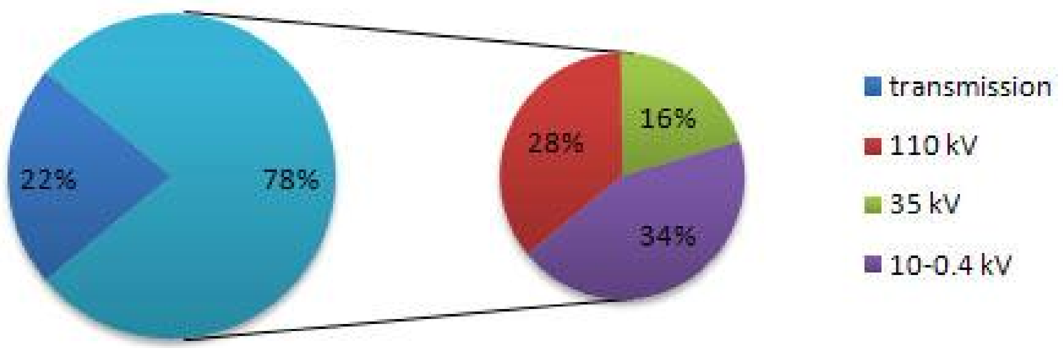
Second category includes customers which interruption could lead to long working delay for people and equipment. The allowable interruption pause should not be over than 30 minutes. Different kinds of industrial equipment, schools and dwelling houses with less than five floors are typical second category consumers. Power supply as in case of first category should be provided but switching between them could be manual.

Third category consists of all other customers, which are not belonging to other categories. Customers of this category supplied with one power supply, but in case of fault or repair interruption time should not be more than 24 hours. [28]

Almost all electricity customers in rural areas belong to third category. In present time the level of reliability of Russian distribution networks is low. The time of interruption is very long. So in 6 – 20 kV lines the average time of recovery the electricity supply are about 2.5 hours. In low voltage networks this value is bigger and equal to 4 – 5 hours. [23]

4.6 Losses

Last years the losses in networks are increasing constantly and this process will continue if some questions in network distribution management don’t be solved. The biggest part of losses falls on Russian distribution networks (110 kV – 0.4 kV lines) and formed 78 % from all network losses and are about $85 \cdot 10^9$ kWh annually. [13] Picture 4.5 depicts the structure of distribution networks losses.



Picture 4.5 Structure of distribution network losses (Source: [23])

There are two types of losses in distribution networks, commercial and technical. As for the technical losses the main cause for its rising is ageing and technical conditions of network components. The reason of commercial losses is weak measurement system, which can not provide adequate results due to morally aged components. Additionally, stealing the electricity is one of the problems in post-Soviet Russia. Turmoil in laws is the main prerequisite for this sad situation.

Nowadays average losses are about 20-25 %, of course, different regions of the country have different values. [13] According to “Project of rules for retail market during transition period” [30], losses which are higher than 10-12 % from amount which is entered the network should be bought by distribution companies for their compensation.

4.7 Economical side

Russian electricity market reform which are now taking place, bring new rules in power sector. Liberalization of the market can provide Russian distribution system with so much needed investments. Distribution companies which are organized on the basis of regional AO-Energos, nowadays have real interest in providing quality and reliable electricity supply. Distribution companies should start preparing for new regulation and penalization algorithms that will be established as soon as possible.

4.7.1 Structure of ownership

All grids can be divided into two main parts, transmission and distribution. Transmission lines belong to IDGC (Interregional Distribution Grid Companies). All transmission grids which fulfil power flowing between different regions with voltage level higher than 110 kV belong to IDGC. Lines with lower or equal voltage level which provide supplying electricity for customers inside the region called distribution. Main part of distribution lines belong to RDGC (Regional Distribution Grid Companies). Also there are a lot of rather small local distribution companies, which accomplish maintaining only medium voltage (6 and 10 kV lines) and low voltage lines.

Additionally, energy supply companies which provide end-users with electricity existed on the new liberalized market. These companies usually own 400 V lines as far as the customer. This situation is typical for domestic customers, who own lines only inside the house.

In other cases customer also own part of 400 V network and sometimes even 6 kV or 10 kV lines, if they are situated on the land owned by customer. This complicates the maintaining of these lines for distribution companies. Firstly, the contract has to be concluded between network owner and distribution company. In future, new customers would have responsibility to keep good technical condition of network by themselves. The boundary of balancing property will pass through 400 V switching device on distribution substation.

Also due to political and economical crises in Russia and consequent conversion from state-planned to market economy a lot of unowned network objects appeared. Part of this network is in municipal rent, and due to lack of investments they could not be properly maintained. The question of its ownership should be regulated in near future.

4.7.2 Renovation plans

Currently, the life time of 40% of lines is over and more than 80% are in need of technical renovation. Losses due to overlimit deterioration increased up to 20-25%, duration of customer's interruption for one feeder is 70-75 hours annually. The average number of faults in overhead lines with less than 35 kV voltage level is 25 faults per 100 km annually. Such conditions of the network call for renovation program, which can solve all the problems which are now existed in distribution networks. [13]

Substations and their equipment, which have been used for more than 25-30 years should be replaced with new ones. About 45 % of power transformers on 6/0.4 kV and 10/0.4 kV substations need to be replaced. Therefore, about 240 thousands of transformers should be replaced by 2015 according to plans of RDGCs. Furthermore about 60 % of old oil disconnectors and 50 % of measuring transformers should be also replaced. [16]

As for the lines over 1 million kilometres of aerial and cable lines have to be replaced by 2015. These plans require 120 thousands of kilometres to renovate annually. More specifically values is listed in table 4.7

Table 4.7 Length of lines in need of renovation and reconstruction (Source: [18])

Voltage level, kV	**Total length, ×10^3 km**	**Including**		
		2001–2005	2006–2010	2011–2015
110	28,2	9,7	10,5	8,0
35	77,7	17,8	20,1	39,8
6–20	910,0	470	120	320
0,38	600,0	450	40	110

The main problem that can disrupt these plans is a financial problem. Permanent sources of money for renovation program should be found. Nowadays in the tariff for electric energy cost of network renovation is added. Investments that are brought to Russian power market by the reform are mainly made in generation and other business, not in the distribution networks. Therefore in near future the main source of money for technical reequipment should become the technical connection fee. Calculated separately for every new customer it includes fee for network reinforcement. Technical connection fee is a real solution for ageing Russian networks. [29]

5 Potential use of 1000 V system in Russia

This part represents the possibilities of using new system in Russian distribution networks. The question of compatibility of network components is observed, could components which are in use at present suit the new voltage level. Possible places of 1kV system implementation in Russia are presented. Suitableness for safety regulation and problem of fulfillment of quality requirements are discussed.

5.1 Compatibility of network components

As LVD in Finland, Russian standards define 1000 V as a low voltage level. So the same advantages can be achieved from this state. Starting from Finnish experience in using the three voltage level distribution system, known that it is possible to use some components without any modifications on 1 kV as they have been already designed to use with low voltage.

Three main types of cables which are used on aerial lines can be applicable with using on 1 kV voltage level. Aerial bundled cable, covered conductors or bare overhead wire could be used in new system. Wires itself could be utilized on 1 kV without any restrictions. The only problem could occur with insulated cables when overvoltages occurred, but reason of this is not a raised voltage. A situation with insulation strength is permanent and even occurs on 400 V voltage level. Lighting overvoltages are the major motive for the insulation violation, this problem are considerably significant on covered conductors, than on aerial bundled cables, due to their insulation durability. As for the poles it is better to use wooden ones, because with concrete poles some problems with safety could occur.

Using new 1 kV distribution system, with all new designed specially for this voltage components would not be a problem. The problems is starting to appear when 1 kV system trying to use on for example on 400 V line, which has been already constructed. Rising of the voltage of an old line could cause a lot of problems, mainly due to insulators, which are technically unsuitable and possible overvoltage could cause a flashover between wire and pole. In case of concrete pole, this situation could be very dangerous, because this pole is conductive and possibility to harm people is existed. Therefore, it is advisable not to use old 400 V structures with 1 kV voltage. Lowering the voltage from 10 kV to 1 kV should not provide any problems.

As 1000 V distribution system is used as isolated, there is no demand for using four-wire cables, and if it is possible three wire cables could be applied without any restriction or modification to the system.

The only proven by Finnish experience way of installation is use aerial bundled cable (e.g. AMKA structure cable) and impregnated wooden poles, this state provide both safety and reliability, on account of cable structure and type of installation. High insulation level and possibility to resist the situation when tree falls on the line made this cable preferred to other possible options.

The situation with transformers is the same as in Finland when 1 kV system has just taken into use. For the first installation targets in Russia, transformers which have been already designed could be used. The 10/1 kV transformers could be quickly designed on the basis of 10/0.4 kV transformers. It will take some time to make an own 1/0.4 kV transformer in Russia, so again transformers that proved themselves in Finnish experience is better to use, to provide good results and then to have positive experience. Possible installation problem could appear, in case when new transformers putted into old distribution substation.

To sum up 1 kV distribution system could be taken into real life exploitation with only slightly modification, moreover Finnish equipment could be used “as is” in Russian distribution networks. The new Russian regulations advice to use pole-mounted distribution substations if the load of transformer is lower than 160 kVA and also only wooden impregnated poles should be used in new construction targets. Therefore that would not be any problems with compatibility of components.

5.2 Fitting safety regulations

Russian safety standards allow using isolated neutral in low voltage networks. So no global constraints in using 1000 V distribution system in Russia are existed. The main requirement in isolated neutral low voltage systems in Russia is to use safety grounding of equipment together with insulation control equipment. [31] Due to possibility of using isolated system in Russia the same protection equipment as in Finland could be used.

If impregnated wooden poles are in use, all three types of cables (bare, insulated overhead, aerial bundled) could be applied, because the body of the pole is not conductive and raising of voltage would not cause any problems, which starts when poles from reinforced concrete are used. The isolators designed for 400 V level can not provide the required level of insulation between conductors and the body of the pole. This is very dangerous situation, because touch voltages in the body of the pole could harm people or animals. Earthing of the poles can solve this problem, because potentials of the ground and the pole will be equal when fault occurs and risk will be minimized. Installing new 1 kV line on the existed 10 kV poles, which always must be earthed according to Russian safety standards is possible. The state when aerial bundled cable with 1 kV voltage is installed on concrete pole should not provide any problems because of strong durability of the aerial bundled cable.

If same equipment as in the 400 V networks would be in use, 1000 V equipment should be perfectly labelled to avoid possible mistakes of distribution company's personnel. Raised voltage level requires more attention during maintaining and fault repairing. So staff should be prepared to work with new voltage level.

5.3 Quality and reliability requirements execution

Nowadays in Russia there are no working penalization mechanisms for those who violate quality or reliability requirements. In addition many laws and regulations became not obligatory to obey. Many of the normative documents need to be corrected and updated to have force in present situation. On the other hand electricity market reform which is taking place should provide new regulation mechanisms, which would oblige distribution companies to pay for long interruptions or for unsatisfactory quality of electricity. In this situation new 1 kV technology would be very useful to help not to cross the border of quality and reliability.

Firstly 1000 V system could greatly increase the reliability of distribution due to providing separate protection area for branch line; consequently faults on it would not cause the whole feeder disconnection. Amount of outages and time of fault localization could be decreased and significant improvement in situation with reliability in Russian distribution networks would occur.

The quality of electricity supply could also be improved. So using the 1 kV line instead of 400 V line considerably decrease the voltage drop at the customer end. And it is easier to provide needed by Russian standards 5 % voltage drop lower limit.

To sum up 1000 V distribution system could increase activities in Russian distribution sector, which would be very important in new liberalized market's conditions.

5.4 Possible installations and market potential

According to Finnish experience of real cases when 1000 V system is used the best and proven by few years of unproblematic exploitation way to use this system is to apply 1 kV instead of medium voltage line. In new construction or in renovation target of low load distribution branch lines 1 kV system could be used. The voltage of medium voltage lines in Russia, which half as lower as Finnish distribution line's medium voltage and equal to 10 kV. Therefore it reduced the economical limit of usage of the 1 kV distribution system, but the technical area is the same as in Finland. So 1 kV system could be implemented in areas where loads are not more than 100 kW and line length is from few hundred meters to few kilometers. The strong dependence between length of the line and transmission capacity existed and consequently the longer is the line the less power could be transmitted. In Russia this situation is even more complicated due to possibility to use 6 kV voltage level, in spite of this voltage is forbidden to use nowadays. Sometimes if old 6 kV line is in need of renovation, then same voltage level will be used to provide more cost-effective solution, e.g. not to change distribution substation buildings or change insulators on the poles. This operation is called retrofit.

In very rural areas in Russia, there are a lot of separate settlements, which due to economical situation in Russia decrease their consumption and consequently there are a lot of low loaded lines and transformers. Additionally these lines are very old and in need of renovation, renewal of these lines on the same technical level is inexpediently. So the potential in this case for 1000 V distribution system is existed.

This typical usage in low loaded lines is not the only one possibility. Then, 1 kV system could be used to divide transforming districts into independent parts, so that faults in one district would not cause outages in other districts. The very common in Russian rural or leisure areas situation when from one transformer with high rated power (e.g. 400 kVA, 600 kVA or even 1000 kVA) a lot of customers are supplied. In this situation fault anywhere lead disconnection of all customers. And usually this fault clearing takes a lot of time. Electricity supply could be organized so, that firstly voltage would be transformed to 1 kV and in the centers of demand 1/0.4 transformers could be applied. This solution could provide savings not only in outage cost, but also might decrease the investment cost because the conductors with thinner cross-section could be used if voltage level would rise.

In spite of big amount of investments in Russian power energy sector caused by restructuring in electricity markets and institutions, the state of distribution networks is not really the best one. In present situation customer needs to pay for network reinforcement to be provided with electric energy and also pay for building of new lines to be connected to the network. Therefore cost-effective solution as 1 kV system could be very useful in such conditions. If 1000 V system could provide less investment cost solution in some customer's case then consequently the technical connection fee would be lower also.

The benefits could also be provided in outage costs, if the algorithm for leving the cost of energy not supplied (CENS) from distribution companies would be established. According to Finnish experience this part of savings three voltage level distribution system is the most significant. In near future when the electricity reform will be canncelled and free market will be established, and the regulation for distribution companies appear it would be a great demand for new ways and technologies for icreasing the reliability of distribution. Hence the 1 kV distribution system might be very useful in such kind situation.

6 Case studies

This part includes case studies about real example in Russia, where 1 kV system is possible to install. Calculations include comparing between standard 10/0.4 kV distribution system and 1000 V distribution system. Comparing is made in voltage drop, investment costs, costs of losses and outages.

6.1 Description of case

The case study example is situated in coast region of Finskiy Zaliv (Suomenlahti). The target system is an example of Russian rural area distribution network. It consists of 35/10 kV substation from which several feeders are gone aside. The target feeder is 11 kilometres long with about 2500 kVA of total power. The branch line that are going to be renovated is 3220 m long and consist of two kinds of conductors, the main length of the line are made with overhead line and remaining part (about 120 meters) with underground cable. In the end of the branch line there is a 10/0.4 kV low loaded substation. On existed substation one 180 kVA transformer is installed, but according to information from distribution company, the average load of this transformer is only 28 % of its nominal power, and correspondingly is equal to 50 kVA. The maximum load of this transformer in peak regimes is 35 % and come to 63 KVA. The information about 400 V customers can not be received and consequently in this survey for simplifiing the calculation it is assumed that there is only one big customer situated about 50 meters far from substation with load equal to 60 kW. More detailed key figures are presented in table 6.1

Table 6.1 Key figures from the target area (Source: “Kurortenergo”)

Definition	**Amount**
Feeder length [m]	10 700
Total feeder power [kW]	2500
Fault rate of the feeder [faults/100 km, a]	30
Maximum power of customers [kVA]	63
Average power of customers [kVA]	50
Length of the 10 kV branch line [m]	3220
Length of 400 V branch [m]	50
Active power of the customer [kW]	60

Other parameters which are used in following calculations are listed in table 6.2

Table 6.2 Calculation parameters

Parameter	**Value**
Lifetime [a]	40
Time of load growth [a]	40
Peak operating time losses [h]	800
Interest rate [%/a]	5
Power factor	0.95
Annual growth of consumption [%/a]	1
Price of power losses [€/kWh]	30
Price of energy losses [€/kWh]	0.03

The situation in this area is so that strong winds from the gulf cause a lot of outages in overhead lines, because they are usually situated in forests. The line path is not in good conditions nowadays and demands for permanent cutting down the trees. The rate of underground cabling in the 10 kV distribution lines which belong to distribution company which is operating in this region are very high. The name of the company is “Kurortenergo”. If in the near future the distribution company decided to renovate this target, it would use an underground cable to reduce the fault rate in the line.

The main idea of the case studies is to compare technical and economical values for two cases. The first case to use firstly 10/1 kV transformer near the feeder, then apply 1 kV underground cable instead of branch line and then near to the customers install 1/0.4 kV transformer to provide them with electricity and the is the traditional solution to use 10 kV underground cable as branch line.

6.2 Selection of components

The selection of the transformers should not provide any problems. Transformers are selected on the basis of the power that is flow throw them. As was assumed the customer has 60 kW load, in that case total power will be equal to 63 kVA as can be calculated using equation (6.1).

$$S = \frac{P}{\cos\varphi} = \frac{60}{0.95} = 63\,\text{kVA} \qquad (6.1)$$

The nearest transformer to this power is transformer with 100 kVA rated power. Transformer should provide transmission capacity for the whole lifetime period. So the equation (6.2) should be right to prove this thesis.

$$\left(1+\frac{r}{100}\right)^{T} < 1.5 \cdot S_{n} \cdot \cos\varphi \qquad (6.2)$$

Where r = the annual percentage of growth of consumption

P = the load of the transformer during the first year of operation

S_n = the rated power of transformer

T = the lifetime period

Coefficient 1.2 is selected because transformers could be installed in old substation, which are building-mounted type.

$$\left(1+\frac{1}{100}\right)^{40} \cdot 60 < 1.2 \cdot 100 \cdot 0.95$$

$$90 < 114$$

With selected calculation values transformers with 100 kVA rated power is acceptable. Therefore all three transformers, 10/0.4 kV, 10/1 kV, 1/0.4 kV are selected with this nominal power. All technical parameters for these transformers can be found in Appendix A.

The selection of the cable should be done properly, because in cable selection there is a great dependence between technical and economical constraints. Cables that are economically reasonable usually won't provide needful transmission capacity or allowed voltage drop. The best way in conductor selection is to use limit curves method, which usually used in medium voltage lines selection but also in low voltage this method could be possible. Equation for this method is (6.3)

$$S > U \cdot \sqrt{\frac{(C_{inv2} - C_{inv1})}{\kappa \cdot C_{h} \cdot (R_{j1} - R_{j2})}} \qquad (6.3)$$

Where C_{inv1} = the investment cost of line 1

C_{inv2} = the investment cost of line 2

R_{j1} = the resistance of line 1

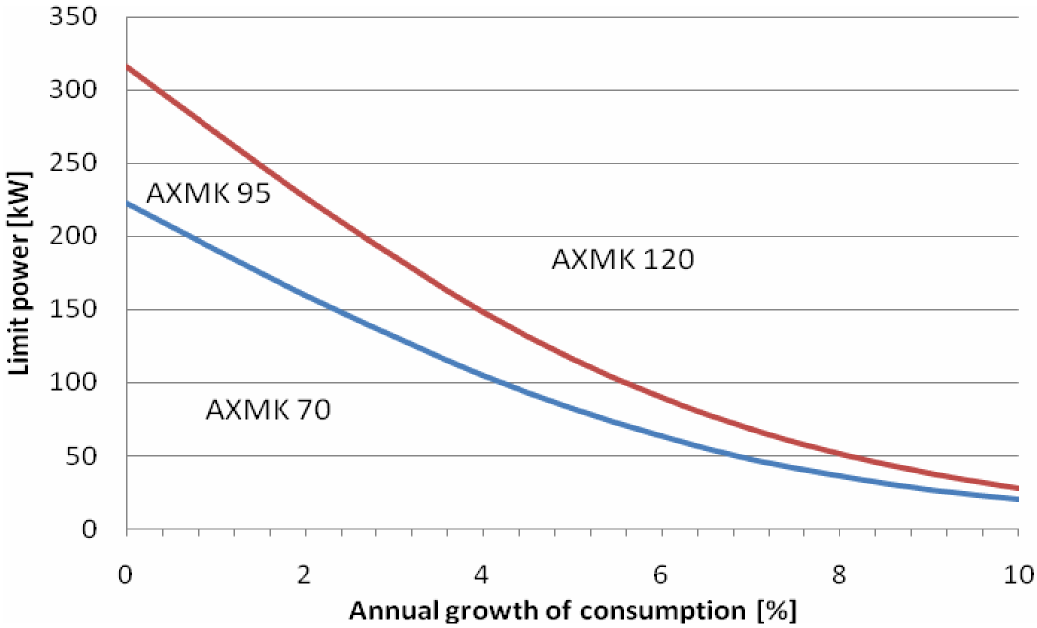
R_{j2} = the resistance of line 2

U = the voltage of the line

κ = discount coefficient

C_h = the price of the losses

Picture 6.1 show limit curves for three underground cables (AXMK 4×70, AXMK 4×95, AXMK 4×120) which is calculated for different annual growth of consumption, based on this curves cable to apply could be selected.



Picture 6.1 Limit curves for AXMK underground cables for 1 kV voltage

According to the picture 6.1 in our case when first year demand is only 60 kW economically defensible to take only AXMK 4×70 cable. But this cable might not be suitable technically. So this case should be investigated properly.

As for the 10 kV underground cable AHXAMK-W 3×70 should be selected because it is the lowest cross-section for cables which insulation suits 10 kV voltages. For the 400 V line the AXMK 4×70 cable could be implemented.

6.3 Voltage drop calculation

Calculation of voltage drop should show that all components are selected right and allowable limit for voltage drop is holding true. Firstly the resistances for all components should be calculated and reduced to 400 V level. Calculation for transformers is made by using equation (6.4) and (6.5)

$$X = x_k \cdot \frac{U_2^2}{S_n} \qquad (6.4) \qquad\qquad R = r_k \cdot \frac{U_2^2}{S_n} \qquad (6.5)$$

Calculation for lines are made according to their length, all rated values for components are taken from tables in Appendix A. Results for all components are presented in table 6.3 and 6.4

Table 6.3 Resistances for the 10/1/0.4 kV distribution system

R (10/1 kV)	X(10/1 kV)	R (1 kV)	X (1 kV)	R(1/0.4 kV)	X(1/0.4 kV)	R(0.4 kV)	X (0.4 kV)
0,028	0,0576	0,247	0,044	0,028	0,0576	0,024	0,00425

Table 6.4 Resistances for the traditional 10/0.4 kV distribution system

R (10 kV)	X (10 kV)	R(10/0.4 kV)	X(10/0.4 kV)	R(0.4 kV)	X (0.4 kV)
0,0023	0,0007	0,0576	0,028	0,024	0,024

Firstly the current *I* need to be determined, assume that voltage in the end of the line is equal to 400 V and then calculate the current using equation (6.6)

$$I = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi} = \frac{60000}{\sqrt{3} \cdot 400 \cdot 0{,}95} = 91{,}2 \text{ A} \quad (6.6)$$

Then the voltage drop could be calculated using equation (6.7)

$$\Delta U = \sqrt{3} \cdot I \cdot (\Sigma R \cdot \cos\varphi + \Sigma X \cdot \sin\varphi) \qquad (6.7)$$

Table 6.5 presents the voltage drop value for different cases, first three for three voltage distribution system with different 1 kV cables and fourth for 10 kV.

Table 6.5 Voltage drop for different cases

Applied cable	**Voltage drop, V**	**Voltage drop, %**
AXMK 4×70	57,14	14,28
AXMK 4×95	44,72	11,18
AXMK 4×120	41,37	10,34
AHXAMK-W 3×70	11,22	2,81

The allowable voltage drop is provided only in fourth case, when traditional voltage system is applied. The 10/1/0.4 kV three voltage distribution system would not provide needful voltage level to the end user. When AXMK 4×70 is applied which is economically efficient, the voltage drop is very high this situation could be solved by applying AXMK 4×95 cable, which significantly decreases the voltage drop, but even in that case it would not provide 5 % limit. The only possibility is to use tap-chargers of the transformers. If tap chargers would be applied the voltage drop at the customer’s end will fit the permissible value.

6.4 Amount and cost of losses calculation

The cost losses calculation consists of calculation losses in transformers an in the lines. P_k and P_0 parameters are taken from Appendix A for selected transformers. As the parameters for transformers are equal and therefore only one calculation is needed. They are presented below.

Firstly annual no-load energy is determined according to the value of rated no-load losses and is equal to:

$$E_{L0} = P_0 \cdot 8760 = 210 \cdot 8760 = 1840 \text{ kWh}$$

Annual no-load costs:

$$C_{1L0} = C_{LP} \cdot P_0 + C_{LE} \cdot E_{L0} = 30 \cdot 0{,}21 + 1840 \cdot 0{,}03 = 61{,}5 \text{ €}$$

Where	C_{LP}	=	cost of power losses
	C_{LE}	=	cost of energy losses

Annuity value for 40 years period:

$$C_0 = C_{1L0} \cdot \left[1 - \frac{1}{\left(1 + \frac{p}{100}\right)^T} \right] \cdot \frac{100}{p} = 61{,}5 \cdot \left[1 - \frac{1}{\left(1 + \frac{5}{100}\right)^{40}} \right] \cdot \frac{100}{5} = 1055 \text{ €}$$

Load losses:

$$P_L = \left(\frac{S_{inst}}{S_n} \right)^2 \cdot P_k = \left(\frac{63}{100} \right)^2 \cdot 1750 = 695 \text{ €}$$

The load loss energy in the first year is calculated:

$$E_L = P_L \cdot t_L = 695 \cdot 800 = 556 \text{ kWh}$$

Load loss costs in the first year:

$$C_{1L} = C_{LP} \cdot P_L + C_{LE} \cdot E_L = 30 \cdot 0{,}695 + 0{,}03 \cdot 556 = 37{,}53 \text{ €}$$

Before calculating the load loss energy costs for 40 years period the discount factor should be calculated:

$$\varepsilon = \frac{\left(1+\frac{r}{100}\right)^2}{1+\frac{p}{100}} = \frac{\left(1+\frac{1}{100}\right)^2}{1+\frac{5}{100}} = 0{,}97$$

$$\kappa = \varepsilon\frac{\varepsilon^T - 1}{\varepsilon - 1} = 0{,}97\frac{0{,}97^{40} - 1}{0{,}97 - 1} = 22{,}77$$

Then the 40 years annuity cost is equal to:

$$C_L = C_{1L} \cdot \kappa = 37{,}53 \cdot 22{,}77 = 855 \text{ €}$$

The total cost of the losses in the transformer is equal to:

$$C = C_0 + C_L = 1055 + 855 = 1910 \text{ €}$$

As for the lines the losses are calculated using equation (6.8)

$$P = 3 \cdot I^2 \cdot R \quad (6.8)$$

The current which is used depend on the voltage level of the line, for cost losses same discount factor as for the transformer's load losses can be used. As the 400 V line are the same in both cases we neglect losses costs in it. The calculation for 1 kV line is given below:

$$P = 3 \cdot 36{,}5^2 \cdot 0{,}165 = 660 \text{ W}$$

$$E_L = P_L \cdot t_L = 660 \cdot 800 = 528 \text{ kWh}$$

$$C_{1L} = C_{LP} \cdot P_L + C_{LE} \cdot E_L = 30 \cdot 0{,}660 + 0{,}03 \cdot 528 = 35{,}64 \text{ €}$$

$$C_L = C_{1L} \cdot \kappa = 35{,}64 \cdot 22{,}77 = 812 \text{ €}$$

Losses in traditional two voltage level are considerably lower and equal to:

$$P = 3 \cdot 3{,}6^2 \cdot 0{,}0023 = 0{,}1 \text{ W}$$

$$E_L = P_L \cdot t_L = 0{,}1 \cdot 800 = 80 \text{ kWh}$$

$$C_{1L} = C_{LP} \cdot P_L + C_{LE} \cdot E_L = 30 \cdot 0{,}0001 + 0{,}03 \cdot 80 = 2{,}5 \text{ €}$$

$$C_L = C_{1L} \cdot \kappa = 2{,}5 \cdot 22{,}77 = 57 \text{ €}$$

The total amount of losses costs for both cases is considerably differ, the three voltage level system has two transformers and 1 kV line so the total costs are equal to 4632 €. As for the traditional system which has only one transformer and 10 kV line with low losses level, their total losses cost is 1967 €.

6.5 Outage cost calculation

The outage costs for the case when branch line is applied with 1 kV line is equal to zero, because faults in the branch line do not affect the whole feeder and other customers. The outage costs could be calculated using equation (6.9)

$$C_{out} = l \cdot f \cdot P \cdot t \cdot C_E \qquad (6.9)$$

Where	l	=	feeder length
	f	=	fault rate
	P	=	feeder power
	t	=	fault repair time
	C_E	=	cost of unsupplied energy

Firstly the discount factor for outages should be calculated:

$$\varphi = \frac{1+\frac{r}{100}}{1+\frac{p}{100}} = \frac{1+\frac{1}{100}}{1+\frac{5}{100}} = 0{,}962$$

$$\kappa = \varphi \frac{\varphi^T - 1}{\varphi - 1} = 0.962 \frac{0{,}962^{40} - 1}{0{,}962 - 1} = 19{,}94$$

The situation when nothing is done to the line is very interesting, so in that case the outages would be:

$$C_{out/a} = 3{,}22 \cdot 0{,}3 \cdot 2500 \cdot 3 \cdot 0{,}61 = 4420 \text{ €}$$

$$C_{out} = \kappa \cdot C_{out/a} = 19{,}94 \cdot 4420 = 88135 \text{ €}$$

When the 10 kV cable is implemented the fault rate becomes about 10 times lower, so:

$$C_{out/a} = 3{,}22 \cdot 0{,}03 \cdot 2500 \cdot 3 \cdot 0{,}61 = 442 \text{ €}$$

$$C_{out} = \kappa \cdot C_{out/a} = 19{,}94 \cdot 442 = 8814 \text{ €}$$

The benefit in outages between traditional and new distribution system is not so bright, because 10 kV cabling that reduced the fault rate was chosen as second option.

6.6 Comparing

All calculated costs is added to the table 6.6 to make a comparison between new 10/1/0.4 kV three voltage level distribution system and traditional 10/0.4 kV solution for the case described earlier. Also the investment costs are added to the table, to simplify the calculation only main equipment is added, such as transformers and cables. All cost for the equipment is taken from Appendix A.

Table 6.6 Comparison between two systems

	10/0.4 kV system	**10/1/0.4 kV system**
	Investment costs	
Transformers	3419 €	6397 €
Lines	96600 €	28658 €
Total	**100019 €**	**35055 €**
	Losses costs	
Transformers	1910 €	3820 €
Lines	57 €	812 €
Total	**1967 €**	**4632 €**
	Outages costs	
	8814 €	0 €
Total cost	**110800 €**	**39687 €**

As can be seen from the table 6.6 three voltage level system more than a half lower total cost then traditional distribution system. The main difference is in the investment costs, due to very high price of medium voltage cabling. The cost of outages also play significant role.

7 Conclusion

During few years of exploitation 1000 V distribution system prove their reliability and economical efficiency in Finland. This experience could be a great basis for implementation this system in Russia, which in near future should face with the same problems in distribution sector. Ageing infrastructure and new mechanisms of regulations of distribution business which could be established in near future, as a part of market liberalization reform would lead to strong market demand in cost effective solutions to improve the reliability of distribution networks. The 1 kV system could be the one of the possible options.

As was analyzed in this master's thesis the 1 kV system has not any technical or other boundaries to be applied in the Russian networks. Safety regulation standards allowed using isolated neutral 1 kV low voltage system. As for the quality and reliability requirements, they also do not provide any constraints. On the contrary 1000 V distribution system should help to solve the problems of quality and reliability in Russian distribution networks.

The potential for apply new system in Russia exists, and the rural areas not the only one place where invention could be applied. Case studies of real example in Russia shows that use 1 kV voltage level between medium voltage and low voltage networks could be very economically effective, even so no penalization algorithms for not supplied energy in Russia has not established yet. Profits that could be gained in investment costs, should be very useful in lack of investments situation.

To sum up, to provide better future for this system in Russia, first experimental installation should be properly projected and built up only with proven Finnish components. After few years of such project exploitation it would be easier to apply it in real life everywhere.

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Appendix A. Technical parameters and cost of transformers and cables

TRANSFORMERS (20/1 kV + 10/1kV)

		rk [%]	xk [%]	R0 [Ω]	X0 [Ω]	Pk [W]	P0 [W]	[VA]	U1n [V]	U2n [V]	Cost [€]
1	30 kVA-ABB	1,95	3,38	0,114	0,383	585	103	30 000	20 500	1 000	2 358
2	30 kVA-ELIN	2,67	2,98	0,117	0,393	800	105	30 000	20 500	1 000	
3	50 kVA-ABB	1,77	3,48	0,056	0,778	885	140	50 000	20 500	1 000	2 703
4	50 kVA-ELIN	2,20	3,34	0,050	0,798	1 100	125	50 000	20 500	1 000	
5	100 kVA-ABB	1,49	3,50	0,022	0,379	1 485	220	100 000	20 500	1 000	3 419
6	100 kVA-ELIN	1,75	3,60	0,021	0,399	1 750	210	100 000	20 500	1 000	
7	200 kVA	1,40	3,75	0,009	0,200	2 800	360	200 000	20 500	1 000	4 156
8	315 kVA	1,24	3,80	0,005	0,127	3 900	520	315 000	20 500	1 000	5 419
9	500 kVA	1,10	4,40	0,004	0,014	6 600	720	500 000	20 500	1 000	7 421
10	800 kVA	0,89	4,60	0,002	0,010	8 500	1 200	800 000	20 500	1 000	8 827
11	1000 kVA	0,92	4,90	0,002	0,008	10 200	1 450	1 000 000	20 500	1 000	11 021

TRANSFORMERS (1/0.4 kV)

		rk [%]	xk [%]	R0 [Ω]	X0 [Ω]	Pk [W]	P0 [W]	[VA]	U1n [V]	U2n [V]	zk [%]	cost [€]
1	10 kVA	3,40	1,70	0,064	0,605	340	40	10 000	1 000	400		705
2	16 kVA	3,00	2,94	0,055	0,416	480	88	16 000	1 000	400		778
3	30 kVA-ABB	2,59	3,05	0,019	0,066	777	100	30 000	1 000	410		918
4	30 kVA-ELIN	2,67	2,98	0,020	0,066	800	105	30 000	1 000	410		
5	30 kVA-AREVA	2,46	2,71	0,020	0,066	737	115	30 000	1 000	400	3,66	
6	50 kVA-ABB	2,18	3,36	0,012	0,134	1 088	184	50 000	1 000	410		1 715
7	50 kVA-ELIN	2,20	3,34	0,008	0,134	1 100	125	50 000	1 000	410	4,15	
8	100 kVA-ELIN	1,75	3,60	0,004	0,067	1 750	210	100 000	1 000	410		2 978
9	200 kVA	1,23	3,91	0,002	0,034	2 450	420	200 000	1 000	400		5 586

1 kV + 0.4 kV lines

		Rv [Ω/km]	R0 [Ω/km]	Xv1 [Ω/km]	Xv0 [Ω/km]	X0 [Ω/km]	cost [€/km]
1	AMKA 3x16+25	2,064	1,491	0,108	0,055	0,074	
2	AMKA 3x25+35	1,3	1,07	0,106	0,045	0,073	
3	AMKA 3x35+50	0,938	0,746	0,104	0,045	0,073	11 520
4	AMKA 3x50+70	0,693	0,533	0,101	0,045	0,071	
5	AMKA 3x70+95	0,479	0,392	0,097	0,045	0,07	15 620
6	AMKA 3x120+95	0,273	0,392	0,092	0,03	0,078	17 920
7	AXMK 4x25	1,3	1,3	0,088	0,088	0,088	
8	AXMK 4x35	0,939	0,939	0,088	0,088	0,088	
9	AXMK 4x70	0,48	0,48	0,085	0,085	0,085	5 200
10	AXMK 4x95	0,32	0,32	0,083	0,083	0,083	8 900
11	AXMK 4x120	0,277	0,277	0,082	0,082	0,082	10 900
12	AXMK 4x185	0,182	0,182	0,082	0,082	0,082	18 847
13	AXMK 4x240	0,135	0,135	0,079	0,079	0,079	21 792

10 kV underground cables

		R0 [Ω/km]	X0 [Ω/km]	cost [€/km]
1	AHXAMK-W 3x70	0,446	0,138	30 000
2	AHXAMK-W 3x120	0,169	0,119	33 236
3	AHXAMK-W 3x185	0,734	0,141	39 675
4	AHXAMK-W 3x240	0,734	0,141	41 888