TAMPERE UNIVERSITY OF TECHNOLOGY

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# THE UTILIZATION POTENTIAL OF LVDC DISTRIBUTION IN THE VATTENFALL DISTRIBUTION NETWORK

Bachelor’s thesis

Examiner: Professor Pertti Järventausta

# ABSTRACT

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Over 90% of electricity supply interruptions are caused by faults of the 20 kV medium voltage network. Often in rural area networks medium voltage branch lines have to be built for individual transformers, since the customers are scattered and the distances are long. These branch lines increase faults which cause interruptions to a whole medium voltage output line. Rural medium voltage networks are typically located in forests and major a part of it was built in the 1950’s – 1970’s, and thus needs to be renewed in the near future. The result of this renewal work must be able to respond to the future requirements in the following 40-60 years and be done as cost-effective as possible.

LVDC distribution is a promising solution for the renewal, the benefits of which are large power transfer capacity with low voltage and improvements to reliability and power quality. The previous tests showed that the LVDC system tolerates medium voltage network autorecloses without an interruption or a voltage drop due to the capacitance of the system. Moreover, it provides an easy connecting point for the distributed generation and energy reserves. However, the LVDC system is a totally new technology in distribution networks and with the present-day converters only a maximum operating time of 15-20 years is achieved, which is 1-2 times less than an average of lifetime of other parts of the distribution network. Power electronics is constantly evolving, so the lifetime will likely grow in the future.

Power electronics enable several new network structures, of which a unipolar point-to-point LVDC system is the solution, which is the easiest option to move to in the perspective of the distribution network company. The power transfer capacity of that system has been calculated in this thesis using voltage drop and maximum load of transfer cable as boundaries. Based on the power transfer calculations and using results of mass computation of the network, are determined the branches of the medium voltage network in the distribution area of Vattenfall Verkko Oy, which can be replaced by LVDC distribution. Depending on voltage drop selection, there are 4216-4767 km branch line sections with a single transformer, which can be replaced. This is 19-22 percent of the entire length of medium voltage network of Vattenfall Verkko Oy. Moreover, it seems to be also technically possible to replace short and low power multi-transformer branch lines with LVDC distribution. Thus, can be inferred that LVDC distribution have a good utilization potential.

# PREFACE

This Bachelor’s thesis was written for Vattenfall Verkko Oy as a part of a research project SGEM (Smart Grids and Energy Markets) and it is included in Task 2.6: Proof of Concepts; Field Tests. I would like to thank Tommi Lähdeaho for a very interesting subject and guidance. Special thanks to Janne Alin for the help in getting the network data and to the rest of staff in Vattenfall Verkko Oy, from whom I have received advices when needed. Thanks also to Reijo Komsi from ABB Oy Drives for enlightening technical details and professor Pertti Järventausta for constructive comments during the work.

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# TERMS AND DEFINITIONS

## Symbols

| | |
|---|---|
| $A_{wire}$ | cross-sectional area of a wire |
| $I$ | current of the cable |
| $I_{wire}$ | current of the single wire |
| $I_{max}$ | maximum current of the wire |
| $I_{max\_wire}$ | maximum current of the single wire |
| $l_{cable}$ | length of the cable |
| $l_{max}$ | maximum length of the DC cable |
| $l_{wire}$ | length of the wire |
| $P$ | input power of the inverter |
| $R_{DC\_wire}$ | DC-resistance of the wire |
| $r_{DC\_wire}$ | DC-resistance of the wire as Ω/km |
| $r_{uni}$ | transfer resistance with unipolar connection |
| $S_n$ | nominal apparent power of transformer |
| $U$ | voltage |
| $U_{AC\_n}$ | nominal output AC voltage of the inverter |
| $U_{DC\_input}$ | input voltage of the inverter |
| $U_h$ | voltage drop of the cable |
| $U_{h\_max}$ | maximum voltage drop in the DC cable |
| $U_{h\_wire}$ | voltage drop of the single wire |
| $U_{DC\_min}$ | minimum input voltage of the inverter |
| $U_n$ | nominal output voltage of the rectifier |

## Abreviations

| | |
|---|---|
| AC | alternating current |
| AXMK | 0,6/1 kV ground cable with PEX-insulation, 4 symmetric aluminum wires |
| DC | direct current |
| Dyn | transformer structure, which causes 30 degree phase shift between primary and secondary and forms a grounded star point of secondary winding |
| EMC | electromagnetic compatibility |
| LVDC | low voltage direct current |
| RMS | root mean square |

# 1 INTRODUCTION

Electricity distribution networks are a central part of society’s infrastructure. Society’s dependence on electricity has increased dramatically in recent decades and the expectations of the quality of power are higher than ever.

The development of distribution networks to a more cost-effective and reliable direction requires constantly developing new solutions. One of the promising solutions is proving to be low voltage direct current (LVDC) distribution. Because of the development of power electronics and decrease in costs, LVDC distribution has started to interest the distribution network companies even more. LVDC is also one topic which develops the distribution networks towards the smart grid, since the system enables easy connecting point for distributed generation and energy storages.

So far low voltage has been applied to electricity distribution only in AC, whereas DC has been given far less attention. For the time being DC technology has been used only for high voltage solutions because of the high costs of the DC systems. However, LVDC distribution would increase power transfer capacity with low voltage cables in the boundaries of the Low Voltage Directive. The LVDC system also improves power quality and reduces customers’ interruptions. [1]

Especially in the rural area networks transformers and customers are scattered, so often 20 kV medium voltage branch lines have to be built for individual transformers. The majority of the distribution networks were built during a time, when reliability was not as significant a factor as minimization of the investment costs and losses. Thus, a large part of the medium voltage branch lines were built across forests and using open-wire lines instead of more reliable cables. Storms and snow loads cause faults on open-wire lines, which has been a significant source of faults throughout the medium voltage line. Furthermore, a significant part of the rural area networks have to be renewed soon because of ageing. Therefore, development of technical solutions and reliability improving have become more relevant issues. [2]

It is possible to replace low-power medium voltage branch lines by LVDC distribution. This thesis presents the unipolar point-to-point LVDC distribution system with four-wire ground cables, which is planned in cooperation with Vattenfall Verkko Oy and ABB Oy Drives. Based on this system calculations of its power transfer capacity are presented. The purpose of this thesis is to determine, based on those calculation results, how large number of medium voltage branch lines with a single transformer can be replaced by LVDC distribution in the distribution area of Vattenfall Verkko Oy, and based on outcomes consider its utilization potential.

## 1.1 Organization of thesis

First in the chapter 2 the thesis introduces the distribution network and its structure. This gives the reader the basis to understand the environment for which LVDC distribution is designed. Chapter 3 presents generally the advantages of LVDC distribution and its possibilities for further development of distribution networks. The challenges brought by this new network technology are also introduced. Chapter 4 presents different solutions of distribution; special focus on a point-to-point LVDC distribution system, which is planned in cooperation with Vattenfall Verkko Oy and ABB Oy Drives. Chapter 5 introduces methods for power transfer capacity calculations in the LVDC distribution system and results using present-day ground gables. Boundary conditions are voltage drop and the maximum load of cable. When limit curves of power transfer are clear, the chapter 6 determines which branches of the network of Vattenfall Verkko Oy can be replaced by LVDC distribution using results of mass computation.

## 1.2 Vattenfall Verkko Oy

Vattenfall Verkko Oy is a part of the Vattenfall AB group. Vattenfall AB is Europe's fifth-largest electricity producer and the largest producer of heat. It is completely owned by state of the Sweden. Vattenfall AB operates in eight countries; Sweden, Finland, Denmark, Germany, Poland, Great Britain, Belgium and the Netherlands. It has a total of 40 000 employees and 7,4 million customers.

Vattenfall Verkko Oy is the second largest distribution network company in Finland. Its operating area is shown in a figure 1.1. It has approximately 395 000 customers and distribution network of altogether over 62 000 km. 22 050 km of it is 20 kV medium voltage network and 38 625 km 0,4 kV low voltage network. There are also 21 520 20/0,4 kV distribution transformers. The Vattenfall Verkko Oy's distribution network consists mainly of sparsely populated area, so development of the rural area network's distribution technology is especially important. [3]

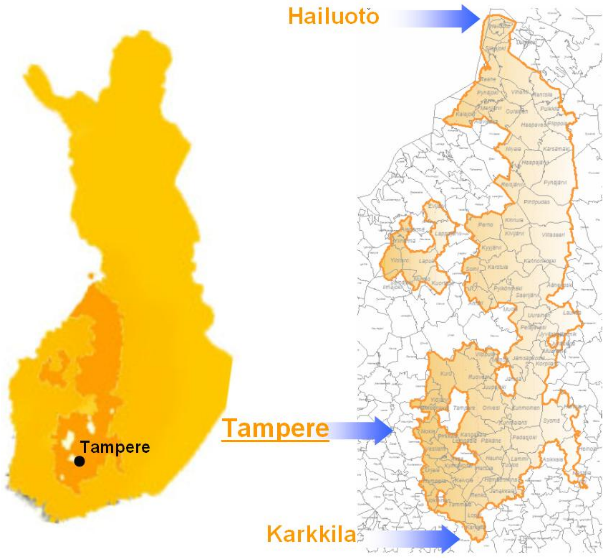


***Figure 1.1.*** *The operating area of the Vattenfall Verkko Oy [3]*

# 2 DISTRIBUTION NETWORK

Distribution networks are a part of society's infrastructure and compose a major part of the electrical network. The technical task of a distribution network is to move electricity to the customers. This electricity can come through the main grid or it can be produced by power plants which are connected directly to the distribution network. Properties of the distribution network affect the customers' power quality and frequency of supply interruptions. Distribution network of a specific area is owned by the area's distribution network company, which is responsible for its maintenance and development. [4]

## 2.1 Distribution network technology

In Finland the electricity distribution networks are currently based on a three-phase AC voltage with nominal frequency of 50 Hz, which is used at a variety of voltage levels. In this three-phase system the phase voltages have a 120-degree phase shift with respect to each other. Use of AC voltage makes altering the voltage level possible using cheap and simple transformers. When the use of AC technology was decided, system with three phases proved to be the best alternative. One of the benefits is the fact that with three-phase system the same power can be transferred with a smaller need of material and lower costs compared to other AC systems. Moreover, an induction motor works directly connected to a three-phase network. The induction motor is the simplest and most commonly used electric motor. [1]

Three different voltage levels are mainly used in the current distribution networks in Finland. These voltage levels are 110 kV, 20 kV and 0,4 kV. The 110 kV voltage level creates the connection between a distribution network and the main grid. Task of the main grid is high voltage (≥ 110 kV) transmission of electrical energy from power plants to closer to the actual consumption areas, where it connects to the distribution network. The main distribution voltages are the 20 kV medium voltage and the 0,4 kV low voltage. In the distribution networks there also are other levels of medium voltage than 20 kV but they are built only in exceptional cases. There is also the newer distribution system based on 1 kV low voltage technology. It is in experimental use and consist of 20/1/0,4 kV AC voltage levels. [1; 4]

Over 90% of electricity supply interruptions experienced by customers are caused by faults of the 20 kV medium voltage network. The remaining approximately 10% of interruptions are caused by the 0,4 kV low voltage network. About 90% of the medium voltage network faults are short-term faults which last a maximum of few minutes. High-speed and delayed automatic reclosing are used to remove those failures. [4]

## 2.2 Structure of the distribution network

Electrical networks can be divided into a radial network and a ring network on the basis of their structure. The loads of the radial network get electricity only via one route. In the ring network the electricity can go through more than one routes. The low voltage networks are nearly always built as radial networks. Crucial parts of medium voltage networks are usually built with the ring structure. However, those medium voltage ring networks are operated like a radial network. The ring structure improves the reliability in fault and maintenance situations since it is possible to provide electricity through several routes. With the ring structure the supply interruptions caused by faults and planned power cuts are shorter or interruption can even be completely prevented. [2]

Different kinds of structures exist for rural and urban networks. Urban networks are almost entirely built with ground cable. Low voltage networks in the centre of cities are often also built using the ring structure. Often in rural area networks 20 kV medium voltage branch lines have to be built for individual transformers, since the customers are scattered and the distances are long. These branch lines increase faults which cause interruptions to a whole medium voltage output line. Especially the replacement of this kind of branch lines using the LVDC distribution system is discussed in this thesis. [2]

Rural medium voltage networks are typically located in forests. The majority of the rural distribution networks were built in the 1950’s – 1970’s. During that time the reliability was not as significant a factor as it is nowadays. Minimization of the investment costs and losses were the main factors which directed the planning of the network. This led to a distribution network topology in which the lines were built directly across the forest. About 90% of the present medium voltage network is open-wire lines from its structure instead of more reliable cable lines. [2]

A significant part of the open-wire lines have to be renewed in the near future because of the ageing. This renewal work has two key challenges. First of all, technical solutions which are able to respond to the expectations for the distribution networks for the following 40-60 years are required. Second, the reconstruction of the networks should be done as cost-effective as possible, so that the costs to the owners and customers will remain at an acceptable level. [4; 6]

## 2.3 Distribution network companies’ role in electricity distribution

Distribution network companies operate locally and own their distribution network. The distribution network companies are obliged to maintain, use and develop their distribution network and secure the supply and sufficient quality of electricity to the customers, which as stated in the Electricity Market Act [5]. Considering quality, the key elements to electricity are reliability and voltage quality. They are determined almost exclusively by the properties of the distribution network. [4]

With the Electricity Market Act the electricity distribution has become its own business area, which is separated from the rest of the electricity and energy businesses. Electricity distribution is a monopoly business, in which each distributor has a monopoly in their own distribution region. Therefore, the economic and technical supervision by the electricity market authorities is related to it. The economic supervision implies for instance that a moderate profit margin to be gained from its business operation is defined for a distributor. The current replacement cost of the network, which depends on the age of the network and amount of new network investments, effects to the profit margin. Therefore, the impact of new technology to the current replacement cost has to be taken into account when considering its large scale utilization. [4]

# 3 EFFECT OF THE LVDC DISTRIBUTION ON THE DISTRIBUTION NETWORK

At the moment the DC power technology is utilized in telecommunication, rail traffic, the electrical systems of ships and the high voltage sea cable systems [7]. Of these, the high voltage sea cables are most closely related to the electric power networks. They are used mainly to power transmission between synchronous regions, which have differing phase or frequency. However, many advantages are gained with LVDC as well. LVDC is one topic which develops the distribution networks towards the smart grid and brings new opportunities to electricity distribution and distribution network development. However, the LVDC system is a totally new technology in the distribution networks, so it brings challenges that must be taken into account.

## 3.1 Advantages of the LVDC system

DC can be used at a higher voltage level because of the definitions of the AC and DC voltage ranges in the Low Voltage Directive. The Low Voltage Directive LVD 2006/95/EC defines the maximum value of low voltage as 1000 VAC and 1500 VDC [7]. Therefore, DC voltage makes larger power transmission possible with the low voltage compared to AC voltage, because the use of the higher voltage level increases the power transfer capacity. When transferring the same power at a higher voltage, the current of the line is reduced. The power loss in the line is proportional to the square of the current value.

The losses are also reduced when using the same RMS voltage level, since with DC, the inductance of the line does not affect in the steady-state, and therefore the reactive power is not transferred at all. Furthermore, the skin effect which increases AC-resistance does not occur in DC. So the DC-resistance is lower than the AC-resistance. Lower resistance means less power losses in power transmission and also higher power transmission capacity. Since DC increases the power transmission capacity of the low voltage, the low-power branches of the medium voltage network can be replaced by LVDC distribution. The use of low voltage cables instead of medium voltage cables reduce both material and construction costs. [1; 7]

The LVDC system brings also benefits during fault situations. The LVDC network forms its own protection area of which faults do not cause interruptions to the entire medium voltage line. Thus, replacement of the medium voltage branch lines to the LVDC system increases the number of protection areas of the distribution network, and therefore reduces the number of interruptions in the medium voltage lines. This improves the reliability of the distribution network. On the other hand, the LVDC system protects customers from medium voltage line interruptions. There is energy stored in the capacitances of the converters and in the LVDC network itself. With this energy the inverter can produce the supply voltage during the high-speed automatic reclosing, so that the customers do not experience interruption or any voltage dip at all. [6]

The LVDC system can also improve the quality of the voltage in a normal operating situation. Active voltage control of the inverter’s output enables nearly constant voltage level at the customer’s connecting point regardless of the voltage fluctuation of the supply AC network. Customer’s voltage level can be kept constant in a very wide DC voltage range of the inverter’s input. Thus, voltage drop does not set as strict limits in the LVDC system as it does in the traditional AC network. This increases the utilization potential of the LVDC system because during a maximum load situation even a large voltage drop can be allowed. [2; 6]

The LVDC system also increases the amount of information in the distribution network which facilitates the use and monitoring of the network. The current converters are able to gather a lot of information about the converter’s input and output currents, voltages and powers. If there is a communication link between the converters and the control room, the converters can transmit real-time information about the distribution system status and quality of the electricity for the Network Control System. This measuring data can also be used for example to identify the route of the fault current and for the fault localization, since potential fault points can be computed using a fault current value and network data. This would simplify and accelerate the removing of a fault. The interruptions could also even be prevented by the active control of inverters when the measuring data is found to be abnormal, before the actual protection works. This is possible since the inverters can measure smaller changes in currents and voltages compared to the actual protection devices. [2; 6; 7]

## 3.2 Possibilities of the LVDC system in the future

The LVDC system brings new opportunities to the distribution of electricity. In the future, energy reserves and distributed generation can be more easily connected to the LVDC network. It is possible to secure the customers’ electricity supply with the energy reserves also during longer interruptions than the high-speed automatic reclosing. The capacity of the energy reserve and the consumption at that time determine the length of the interruption that can be prevented.

Using the LVDC system as the connecting point of the distributed generation brings many benefits. If a rectifying bridge of the rectifier is made with active switching components, power can be transferred in both directions. In this case, the generation can be connected to the DC network and one centralized converter takes care of the synchronization to the AC network. This reduces the total amount of the power electronics which is needed for connecting the distributed generation to the distribution network, so that reduces the costs. The LVDC system can receive more generation capacity than the traditional 400 VAC network, which enables larger generation units to be connected to the low voltage network. This is due to the LVDC system's higher power transmission capacity and possibility to adjust electrical values with the converters. [6]

In addition to the easier network connection of the distributed generation, another advantage is an opportunity to island mode operation of the LVDC system. The customers of the LVDC system would be possible to supply even longer periods of time only with the power of the local generation during an interruption in the supply of the medium voltage network. This of course requires, that the local generation is enough to cover the power consumption and it is possible to keep both the generation and consumption in balance. In normal operation, the energy storages and local generation can be used to balance the power consumption and the power supply of the medium voltage network. [2; 8]

In the future, household and industrial customers can also be connected directly to the DC connection. In industry and, for example, in apartment houses the electricity must be usually transferred long distances with the low voltage, which causes losses and requires use of the heavy-gauge wires. To reduce these losses, the use of the LVDC system would be a viable solution. In that case, the need for an inverter can be entirely avoided, which reduces the construction and maintenance costs of the LVDC system. Also the power losses of the equipment are decreased by the inverter's losses amount. [6]

Majority of the households' electricity-consuming devices, such as electronics, lightning and electric heating are suitable to be used with DC, either directly or through little changes. Induction motors, which are widely used in the industry, require AC to function. However, most of induction motors today are driven using electric drives, which produce the required AC voltage from a DC intermediate circuit with an inverter bridge. Therefore, induction motors can be sourced with DC voltage and it might actually make the motor drives' structure simpler since no rectifying bridge is required. Thus, devices do not cause major challenges when considering DC supply for either household or industrial customers. [6]

## 3.3 Challenges of the LVDC system

The utilization of the LVDC system in the distribution network requires the use of power electronic converters. These rectifiers and inverters have not been used before in the distribution network, so from that point of view the LVDC distribution system is a completely new technology. New technology always brings new challenges and technical and economical risks which must be taken into account.

The LVDC distribution system increases the total number of components of the distribution network. The LVDC system at least requires a transformer, a rectifier and an inverter. Power electronic devices are sensitive to over voltages, and moreover, the growing number of components may expand the total number of faults. Furthermore, a greater number of components means more potential fault points, so the fault localization can become more difficult without the real-time information about the state of the converters. [6]

The operation of the converters' switching components causes harmonic waves which may impair the voltage quality both in the customers and the supply AC network. However, the decrease in voltage quality is not so significant that the harmonics would be an obstacle to the implementation of the LVDC system. Frequencies and amplitudes of the harmonics depend on the switching components of the converter and their control. Usually, harmonic filters are connected with converters for reducing harmonics. Use of these filters weaken the efficiency, complicate the structure of the converters and raise the price of the system. [1; 2]

The use of power electronics causes losses and maintenance costs. Further, when parts of the 20kV medium voltage line are replaced with the LVDC system, losses of power transfer will increase due to lower level of voltage. Besides the LVDC system construction costs, the costs from maintenance and losses should be considered when evaluating economical profitability of the LVDC system.

Power electronics have been used extensively in the industry. According to experiences received from there, the reliability of power electronics is high. However, the operating life of the converters is considerably shorter than other components in the distribution network. In industry, the mean time before failure is typically 5-10 years. Especially, a lifetime of the converter's capacitors and fans affect the operating life of the converter. Therefore, the lifetime of the converter can be increased with a maintenance program and a converter's self-diagnostics. With the present-day converters, it is possible to achieve a maximum operating time of 15-20 years. Still, converters must be replaced an average of 1-2 times during the lifetime of other parts of the distribution network, which is about 30-50 years or even more. Power electronics is constantly evolving, so the lifetime will likely grow in the future. [6; 9]

Operating conditions of the converters vary much more in the LVDC system than in industry. Converters are generally used at nearly constant temperature in the industry, but converters in the LVDC system are exposed to large temperature changes. Thus, in an ideal situation converters should tolerate ambient temperature fluctuations at least in the range of – 35 to + 35 degrees Celsius. Therefore, attention towards good insulation and ventilation needs to be paid when designing the converter's cabinet.

## 3.4 Vattenfall's LVDC research and experiences

Research of the LVDC system utilization in distribution network started in the cooperation of Vattenfall Verkko Oy and ABB Oy Drives in 2008. The first LVDC system was implemented in the network by March 2010. Principle of this LVDC system is similar to DC-link, but rectifier and inverter are side by side so the DC cable in between is very short. Purpose of LVDC test was to examine the operation and influence of power electronics as a part of the distribution network. The site, which was chosen for the test, had previously had complaints due to voltage fluctuations and flicker, caused by long transmission distances and high loads. [10]

The tests showed that the customers’ voltage quality improved thanks to the LVDC system and customers themselves were really satisfied with the power quality. In addition, the LVDC system tolerates medium voltage network autorecloses without an interruption or a voltage drop due to the capacitance of the system. The only complaint came from the inhabitants of the test site because of the acoustic noise, which was caused by the cooling fans of the converter cabinet. Besides noise from the fans, the switching components in the converter cause noise which depends on their switching frequency. Therefore, a good enough acoustic insulation must be considered when installing the converters near settlement. The positive experiences and results are the motivation to continue the research and development of LVDC distribution towards wider scale utilization in the distribution network. [11; 12]

# 4 NETWORK SOLUTION OPTIONS OF THE LVDC DISTRIBUTION

Figure 4.1 presents the low voltage distribution solutions, which are currently in use in Finland's distribution network and the most important solutions that are under study. Solution a) is the traditional way in which 20 kV medium voltage is transformed with a 20/0,4 kV transformer into the 400 VAC distribution voltage. This does not include any power electronics but is based entirely on the using of distribution transformer with a simple structure. Its advantage is low total losses, because electric power is transferred near consumption with 20 kV medium voltage and losses of the transformers are small. However, the branch lines that had been built with open-wires are susceptible to faults and are the cause of a significant part of interruption costs.

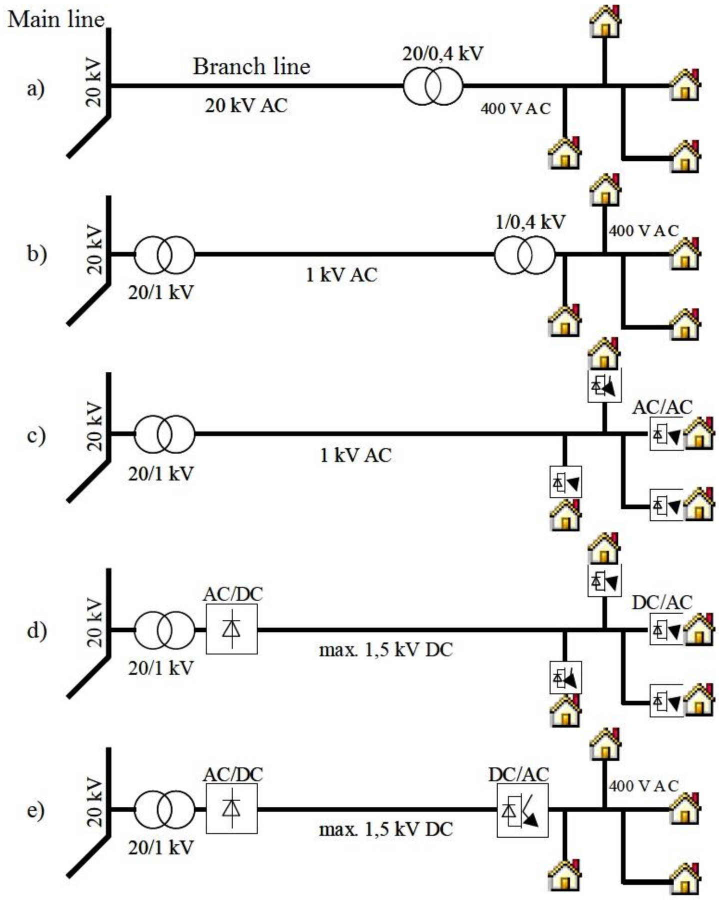


***Figure 4.1.*** *Example solution of low voltage distribution which has been realized with a) the traditional 20/0,4 kV AC technology; b) the 20/1/0,4 kV AC technology; c) the 20/1 kV AC technology and 1/0,4 kV conversion in customer's connecting point with inverter; d) the LVDC system, which maximum DC voltage is 1500 VDC or ±750 VDC; e) the point-to-point LVDC link. [12]*

In the solution b) has been presented the 1 kV AC solution, as an advantage there are possibility to use the maximum voltage level of the low voltage with AC and a new protection zone, which is formed by the 1 kV cable section. The protection zone and the replacement of the open-wire line by the low voltage cable improve reliability a lot, but losses increases when the 20 kV branch line is changes by the 1 kV cable. The solution requires the transformers with new transformation ratios in the network and increases the total number of transformers. The solution is mainly in small-scale use at the moment.

Power electronics enables several new network structures. Solutions c), d) and e) utilizes power electronics and those have not yet been used in the distribution network with the exception of a few test pilots. In the solution c) low voltage power transmission is realized by 1 kV AC voltage and DC voltage is not used to transmission at all. 1 kV AC voltage is not converted to 400 VAC until the customer's connecting point, so losses are reduced compared to the solution b). In the customer's connecting point there is a customer-end inverter which converts 1 kV AC voltage to 400 VAC distribution voltage. The inverter can also improve the voltage quality and enables a control of the voltage level.

Solutions d) and e) are utilized the LVDC technology. The solution d) is perhaps the most studied LVDC solution and its implementation options are discussed more in chapter 4.1. In that option, 20/1 kV transformer produces a suitable voltage level to the rectifier from which the power is transferred with DC. On the customers' connecting point there is a customer-end inverter which changes the DC voltage to 400 VAC distribution voltage. This solution utilizes DC transmission as effective as possible but requires own inverter each customer's.

Solution e) differs from solution d) in that a conversion DC to AC is realized simply with one centralized inverter instead of several small inverters. So customer's connecting point does not need the inverter but DC transmission is not used as effectively as in the solution d). The LVDC distribution system planned for the Vattenfall distribution network is based on the solution e), which is discussed more in the chapter 4.2. Also the LVDC pilot, which experiences was presented in the chapter 3.4, is close to this solution. [13]

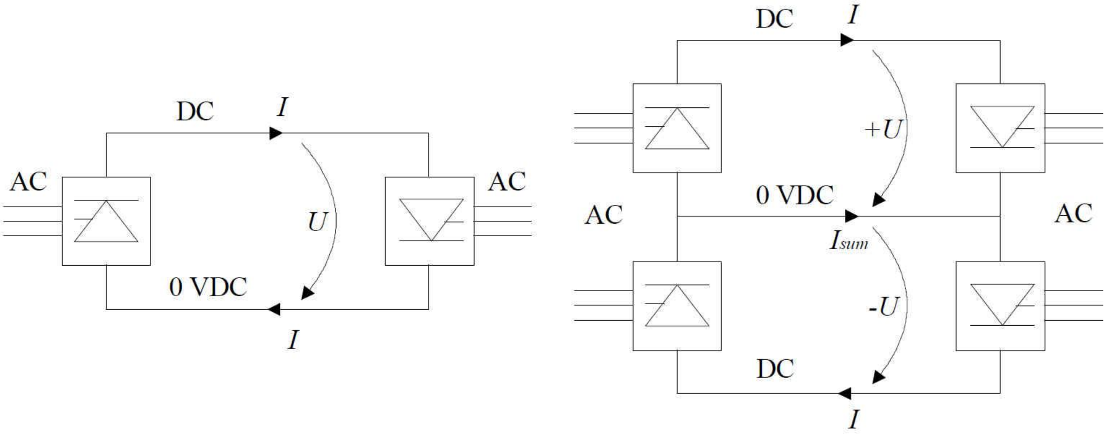
## 4.1 General transmission structure of the LVDC distribution

The power transmission with LVDC can be implemented with different options of the power electronic converters and DC conductor structures. This thesis does not focus the precise structure of the converters, but the unipolar and bipolar options of the DC power transmission are presented more specifically, because the number of conductors and possible voltage level of LVDC depends on the option which is used. These options are presented with help of the figure 4.1 d) solution because it utilizes LVDC power transmission as efficiently as possible.

### 4.1.1 Unipolar and bipolar connection in the LVDC power transmission

DC power transmission can be realized with an unipolar or a bipolar connection. In unipolar connection there are two conductors; the one is outgoing conductor and the other is return conductor of current. In this case, there is one voltage level for power transmission, which can be 1500 VDC in maximum according to the Low Voltage Directive.

The bipolar connection is realized with two voltage level. Absolute values of these voltage levels are the same but the voltages are opposite signs compared to the common zero-voltage level. Therefore, with the bipolar connection the maximum voltage levels allowed by the Low Voltage Directive are ± 750 VDC. The bipolar connection requires three conductors because the zero-voltage level needs its own conductor also. The structures of the unipolar and the bipolar connections are presented in the figure 4.2. [1; 7; 12]



a) b)

***Figure 4.2.*** *The structure of a) the unipolar connection; b) the bipolar connection. The Low Voltage Directive allows a maximum value of U in the option a) U = 1500VDC; b) U = 750VDC. [2]*

### 4.1.2 Network solution with the customer-end inverter

The figure 4.3 presents the LVDC distribution system as part of the distribution network implemented by the unipolar and the bipolar connection. In both solutions the 20 kVAC medium voltage is first transformed to 1 kVAC with 20/1 kV transformer. This 1 kVAC voltage is more suitable for the input of the rectifier. If 20 kVAC voltage is used as the rectifier's input voltage, it requires dimensioning the components of the rectifier to much higher voltage and would also make the structure more complex, making it not sensible economically. Furthermore, adapting of the Low Voltage Directive would not be no longer possible, if the input voltage of the rectifier is over 1000VAC.

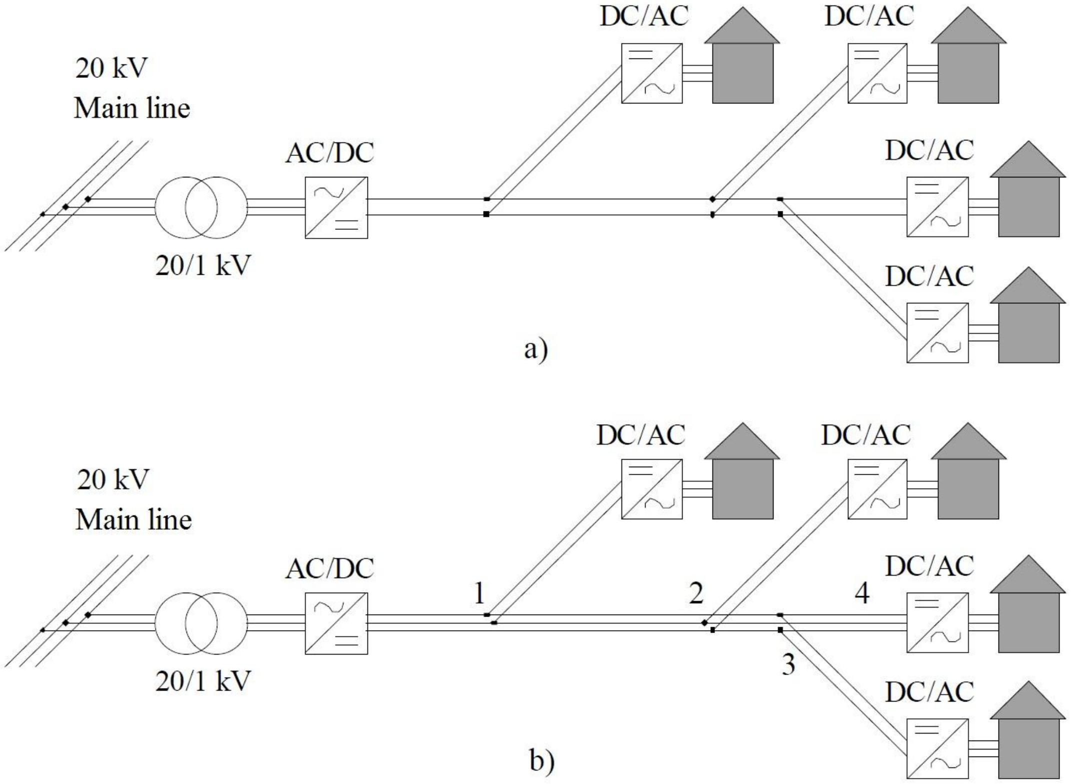


***Figure 4.3.*** *The LVDC system in the distribution network, when it is implemented with a) the unipolar connection; b) the bipolar connection. Like in the figure b) is presented, using the bipolar connection the inverter can be connected to 1) between the zero and the positive voltage; 2) between the zero and the negative voltage; 3) between the positive and the negative voltage; 4) all three voltage level. [2]*

The figure 4.3 a) presents the LVDC system with unipolar connection. In this solution the rectifier produces one voltage level which transfers the power to the customer-end inverters. These inverters convert DC to the 400 VAC distribution voltage for the customers. The converters of the unipolar system have a two-level structure.

The bipolar LVDC distribution system is presented in figure 4.3 b). The rectifier produces three different levels of DC voltage (+750V, 0V, -750V). The inverters can be connected to these voltage levels in three different ways. The first option is to connect the inverter between one or the other DC voltage level and zero (figure 4.3. No. 1 & 2). Another option is to connect the inverter between the positive and the negative DC voltage when the situation corresponds to the 1500 VDC unipolar connection (figure 4.3. No. 3). The third option is to connect the inverter to all three voltage levels (figure 4.3. No. 4). Then the structure of the inverter also must be a three-level in addition to the rectifier. The advantage of the bipolar system is that if the one or the other DC voltage connection is missing, there can still be used the inverters which are connected to the existing DC voltage. One DC voltage can be missing, for example, during the fault or maintenance situation. There can be found more information of the three-level converters and the bipolar system in a reference [7]. [2; 7]

## 4.2 Point-to-point LVDC solution in the Vattenfall distribution network

The Point-to-point LVDC system is the solution which is the easiest option to move to in order to achieve the benefits of the LVDC distribution from the perspective of the distribution network company. This is due to the fact that the present distribution transformer can be replaced by a centralized inverter, when the low voltage network can be kept unchanged. The majority of the low voltage network in the rural area has been implemented by AMKA cable (1 kV aerial bundled self supporting cable), which cannot be used at least at the moment in the LVDC system. The currently valid AMKA cable standard SFS 2200 does not define AMKA's use with DC voltage [1]. The point-to-point LVDC solution does not require changes in the customer-end either, since there is no need for inverter.

The figure 4.1 e) presents the general structure of the point-to-point LVDC system. In cooperation with Vattenfall Verkko Oy and ABB Oy Drives is planned the solution in the Vattenfall distribution network, which is presented in a figure 4.4. This solution differs from the general model in several ways. Instead of a 20/1 kV transformer a 20/0,63 kV transformer is used between medium voltage and low voltage. After that there is a DC-link between a rectifier and an inverter as the general solution, but a DC voltage of 900 VDC is used for the power transmission. After the inverter there is a transformer and an EMC filter unlike in the general structure.

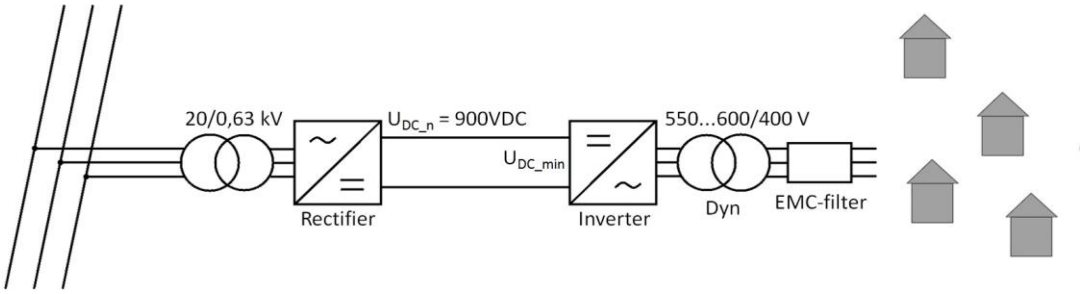


***Figure 4.4.*** *The point-to-point LVDC distribution system designed by cooperation of Vattenfall Verkko Oy and ABB Oy Drives.*

20/0,63 kV transformer supplies suitable input voltage level for the rectifier, allowing the rectifier's operation in nominal operating range. The rectifier is two-level bidirectional power converter with DC voltage intermediate circuit, which can also boost the output DC voltage if necessary. Therefore, it is able to keep the DC voltage almost constant even during the voltage dips. The dimensioning of the rectifier can be done according to effective power of transfer, since the DC cable does not transfer reactive power at all. The rectifier's output is unipolar voltage of 900 VDC.

A voltage of 900 VDC has been chosen, since it is the maximum allowed DC voltage with current low voltage ground cables, as described in the SFS cable standards 4879, 4880, 5800 and 5546 [7]. Also the unipolar connection brings advantages compared to bipolar connection with the point-to-point solution. Maximum power transfer capability can be achieved by using four-wire ground cables, when connected to two wires in parallel, as in the figure 4.5. Thus, ordinary ground cables can be used in the LVDC distribution system as efficiently as possible, because the transfer requires only two different voltages and conductors. The two-level converter also has a simpler structure than three-level converter and therefore it contains less components and may have a better reliability. The advantages of three-level systems come up mainly when used in LVDC distribution systems, such as the system in figure 4.3 b).

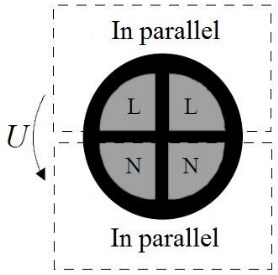


***Figure 4.5.*** *The connection method of four-wire ground cable in the unipolar LVDC distribution system. [1]*

The inverter is a two-level bidirectional power converter with DC voltage intermediate circuit, like the rectifier. Because of the bidirectional converters, power can be transferred in both directions, also from the low voltage network to the medium voltage network. Thus, the distributed generation can be easily connected to this kind of LVDC system in the future.

After the inverter a Dyn transformer is required, because low voltage AC network will be kept unchanged. Dyn transformer makes an earthed star point in the network like the distribution transformer does in the present system. This enables the proper operation of the low voltage AC network and its protection. Majority of the consumers' devices are connected with a single-phase connection, which requires a zero conductor in the low voltage AC network. [15]

### 4.2.1 Reduction of harmonics and disturbances

Both the beginning and the end of the LVDC-link is the transformer that together creates a galvanic isolation of the LVDC system from the AC network. The galvanic isolation shut out common mode harmonics from both the supply and the low voltage AC network and improves the safety of the LVDC system's fault situations.

The EMC-filter at the end of the LVDC-link is connected the star point of Dyn transformer. It includes inductors and capacitors that filter out high-frequency disturbances of 150 kHz – 30 MHz frequency range. The EMC-filter keeps the disturbances below the limits of EN 61800-3 standard, which defines the high frequency disturbance limits of public distribution network. The high-frequency disturbances interferes electronic equipment of customers'. If a load of the LVDC system is, for example, only the electric motors, the filter can be omitted. [15]

### 4.2.2 Protection and dimensioning of the inverter

Unlike the rectifier, the inverter cannot be dimensioned according to effective power, but short-circuit current determines its dimensioning. This is due to the fact that in a short-circuit situation the inverter is able to supply only 120% of its nominal current, but a traditional fuse protection of low voltage AC network requires fairly high fault current to operate correctly. For example, a 50 A fuse requires at least a 250 A short-circuit current to operate according to the five second rule, which is followed when planning a new low voltage network nowadays [14]. For this reason, the inverter has to be dimensioned larger than the power supply capacity would require.

The short-circuit current supply capability of the inverter is also one factor that affects the dimensioning of the inverter's output voltage and, by extension, the dimensioning of the Dyn transformer's primary voltage. The higher the primary voltage of the Dyn transformer, the larger the transformation ratio, because the secondary voltage of the transformer must be the distribution voltage of 400 VAC. The larger the transformation ratio, the higher the transformer raises the current from inverter's output to transformer's secondary. Thus, as high a current supply capability of the inverter is not required if the transformation ratio is big. A high nominal primary voltage of transformer requires also as large nominal output voltage of the inverter. The output voltage is produced from input DC voltage of the inverter, so the input DC voltage must remain closer to its nominal value. This restricts the transfer distance of the LVDC link, because a maximum allowable voltage drop determines how long the DC cable can be between the converters.

The minimum input voltage of the inverter ($U_{DC\_min}$) can be calculated from the nominal output voltage ($U_{AC\_n}$) using the following equation:

$$U_{DC\_min} = 1{,}03\sqrt{2} * U_{AC\_n} \tag{4.1}$$

Coefficient of 1,03 in the equation is a safety margin which prevents too tight dimensioning of the inverter. According to this equation, a nominal output voltage of 600 VAC requires at least an input voltage of 874 VDC. Thus, voltage is allowed to drop only 26 VDC from its nominal voltage level of 900 VDC, which means a 2,9% maximum voltage drop. If nominal output voltage of the inverter is 550 VAC, a 99 VDC voltage drop across the DC cable is allowed, thus meaning a 11% maximum voltage drop. The optimal point between the short-circuit current supply capability and the allowable voltage drop will be set the nominal output voltage level of the inverter probably between 550-600 VAC. [15]

### 4.2.3 Efficiency and losses of the LVDC distribution system

Since the LVDC system is composed of several components, the losses are higher than the traditional distribution system with one transformer. Both transformers of the LVDC distribution system, which are presented in figure 4.4, can be estimated efficiency of 98,5%. Both the rectifier and inverter efficiency is approximately 97,5 % in the nominal operating point of converters. [15] The EMC-filter causes very little losses, so those can be ignored in this estimate. Multiplying the efficiencies of the LVDC system's components with each other gives to overall efficiency of the equipment, which according to those values would be approximately 92%. Losses of the equipment also need to be added the resistive losses of the DC cable when examining total losses of the LVDC system.

In this thesis, the cost of losses is not considered. Calculations of the LVDC distribution system construction and life cycle costs as well as losses analysis compared to the current solution can be found in the Master's thesis of Viivi Naakka, titled Reliability and Economy Analysis of the LVDC Distribution System. The thesis will be completed in early 2012. [15]

### 4.2.4 Point-to-point LVDC distribution system as part of the traditional low voltage network

The distribution transformer can be approximately a kilometer away from customers in the current low voltage distribution system, so that the distribution is implemented in a sensible way according to the construction costs and losses in transmission. However, especially in sparsely populated area there will be situations where, for example, one new customer is 1,5 to 3 kilometers away from the nearest distribution transformer and it is likely that there will not be other customers in the area. The construction of the new medium voltage branch with a transformer or the point-to-point LVDC distribution system like in figure 4.4. would be an unreasonable expensive solution for one consumer. In this case, one low voltage output line could be constructed from the nearest distribution transformer so that it would constitute LVDC link, which allows longer transmission distances. This kind of solution is presented in figure 4.6. The solution is also useful when customers are on an island. Usually, there are only a few summer cottages, but transfer distance can easily be over a kilometer.

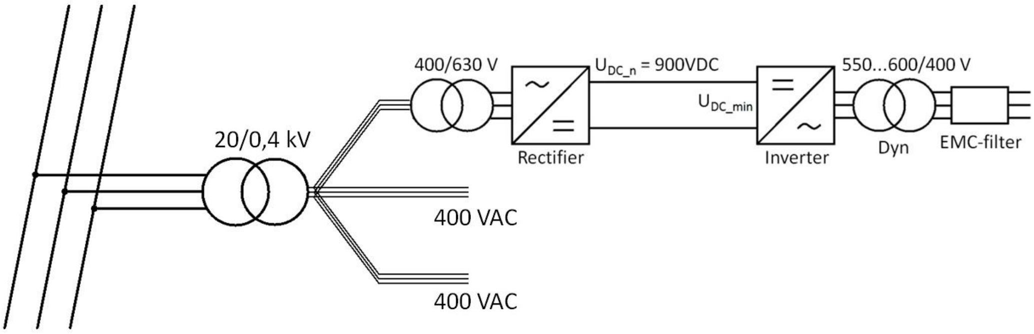


***Figure 4.6.*** *The LVDC distribution system as a part of traditional low voltage network.*

This LVDC link structure is otherwise identical to the figure 4.4 system, but 20/0,63 kV transformer is replaced by a 400/630 V transformer, since now it is connected to low voltage network of 400V. Therefore, calculation results for transmission distance of the LVDC distribution system in chapter 5 are accurate for implementations similar to those described in figures 4.4 and 4.6. [15]

# 5 TRANSFER CAPACITY CALCULATIONS OF THE LVDC SYSTEM

The purpose of the calculations is to solve the transfer capacity of four-wire ground cables in the LVDC system presented in the figure 4.4. The calculations are made with three different voltage drop values and three cable types, which have different cross-sectional area. Based on those calculations can be plotted curves, which are presented power transfer as a function of transfer distance. The inverter's techno-economic sensible dimensioning, wanted power transfer capacity and limitation of the transfer losses determine to which the value of the maximum voltage drop will be limited to. Power and distance of transfer are determined which cable type should be selected.

## 5.1 Calculation methods

Input voltage of the inverter is smaller than the output voltage of the rectifier by the amount of DC cable's voltage drop. As explained in the chapter 4.2.2, nominal values of the inverter are determined how large the maximum voltage drop can be. Maximum voltage drop of the DC cable determines its maximum length. Voltage drop depends only on the DC-resistance and the amount of current flowing through the cable and thus based on the Ohm's law can be written for a single wire of the cable:

$$U_{h\_wire} = R_{DC\_wire} I_{wire}, \tag{5.1}$$

where $U_{h\_wire}$ is voltage drop of a single wire (V), $R_{DC\_wire}$ is DC-resistance of the single wire (Ω) and $I_{wire}$ is current of a single wire (A).

The resistance of the wire depends on its length, material, cross-sectional area and operating temperature. However, the DC-resistance as Ω/km at a temperature of 20 degrees Celsius is known for a particular type of ground cable. Therefore, $R_{DC\_wire}$ can be calculated using equation:

$$R_{DC\_wire} = r_{DC\_wire} l_{wire}, \tag{5.2}$$

where $r_{DC\_wire}$ is DC-resistance of the wire (Ω/km) and $l_{wire}$ is wire's length (km). Since the zero wire of the four-wire ground cables using by Vattenfall Verkko Oy is similar to the phase wires, equations (5.1) and (5.2) give the same result on all four wires of the cable. Thus, combining equations (5.1) and (5.2) the following can be written for the length of all the wires:

$$l_{wire} = \frac{U_{h\_wire}}{I_{wire} r_{DC\_wire}} \tag{5.3}$$

In the unipolar LVDC distribution system the four-wire ground cable is connected to two wires in parallel, as presented in the figure 4.5. Therefore, the one pair of wires operates an outgoing conductor and the other operates return conductor of current. When calculating the voltage drop of the DC cable, voltage drop in both the outgoing and the return route of current must be taken into account. Parallel connection of wires halves the resistance compared to the single wire. However, when considering both outgoing and return conductors, the length of the current's route and thus the resistance is doubled. These cancel each other out, so with the unipolar connection the entire transfer resistance between rectifier and inverter is equal to the cable's one-wire resistance. Therefore, the following can be written:

$$r_{uni} = r_{DC\_wire}, \tag{5.4}$$

where $r_{uni}$ is the transfer resistance with unipolar connection. Formation of the unipolar resistance is further discussed in the reference [1], where the same conclusion has been reached in the equation (3.3).

Based on the equations (5.3) and (5.4), the length of the DC cable in the unipolar LVDC distribution system can be calculated using the following equation:

$$l_{cable} = \frac{U_h}{Ir_{uni}} = \frac{U_h}{Ir_{DC\_wire}}, \tag{5.5}$$

where $l_{cable}$ is the length of the cable (km), $U_h$ is voltage drop of the cable (V) and I is current of the cable (A).

When calculating the maximum limit of power transfer as a function of transfer distance, the voltage drop is kept in the chosen maximum value and maximum lengths of DC cables are calculated using varying values of power. Therefore, the equation (5.5) can be written as:

$$l_{max} = \frac{U_{h\_max}}{Ir_{DC\_wire}}, \tag{5.6}$$

where $l_{max}$ is the maximum length of the DC cable (km) and $U_{h\_max}$ is the maximum voltage drop in the DC cable (V). Since $U_{h\_max}$ is a constant value during a calculation and the $r_{DC\_wire}$ can be found in the cable's data, the only missing parameter is the current I.

Since DC voltage remains constant, the transferred power determines the current. Thus, if the input power of the inverter is denoted P, the current can be calculated using the following equation:

$$I = \frac{P}{U_{DC\_input}}, \tag{5.7}$$

where P is the inverter's input power (W) and $U_{DC\_input}$ is input voltage of the inverter (V).

When voltage drop is kept at the maximum value during calculation, then the inverter's input voltage is at its minimum value and equation (5.7) can be reformulated:

$$I = \frac{P}{U_{DC\_min}}, \tag{5.8}$$

where $U_{DC\_min} = U_n - U_{h\_max}$, where $U_n$ is the nominal output voltage of the rectifier (V).

When the equations (5.6) and (5.8) are combined, the following can be solved for the maximum length of power transfer:

$$l_{max} = \frac{U_{h\_max}U_{DC\_min}}{Pr_{DC\_wire}} = \frac{U_{h\_max}(U_n - U_{h\_max})}{Pr_{DC\_wire}} \tag{5.9}$$

Wires have a maximum current limit, above which the load current should not rise. When the value of power rises high enough, the current in equation (5.8) reaches the maximum limit, therefore the equation (5.9) can no longer be used. After the current limit is reached, the calculation for larger values of power needs to be proceeded by keeping the load current constant instead of the voltage drop. In this case, since the power is supplied using the maximum value of the current, the $U_{h\_max}$ has to be calculated using the input voltage of the inverter:

$$U_{h\_max} = U_n - U_{DC\_min} = U_n - \frac{P}{I_{max}}, \tag{5.10}$$

where $I_{max}$ is the maximum current in the wire (A).

Combining equations (5.9) and (5.10), the equation of the DC cable length can be written:

$$l_{max} = \frac{U_n I_{max} - P}{I_{max}^2 r_{DC\_wire}} \tag{5.11}$$

During calculation power values are increased until $U_{h\_max}$ reaches a value of zero, and thus the transfer distance is also reduced to zero. The transfer distance can be calculated for all values of power, which can be transferred within the maximum current limit of the cable, using equation (5.9) and (5.11).

## 5.2 Power transfer capacity of the LVDC system

Power transfer capacity of the LVDC distribution system is calculated with three different types of AXMK aluminum cables, AX50, AX95 and AX150. Vattenfall Verkko Oy uses these cable types to construct new low voltage AC network and those are suitable also for the use of 900VDC. Data of these cables is listed in table 5.1. The maximum current of a single wire can be found from the cable data. Since the current in unipolar connection is divided between two wires, the maximum current of the cable $I_{max}$ is double compared to a single wires' maximum current $I_{max\_wire}$. $A_{wire}$ is the cross-sectional area of a wire.

***Table 5.1.*** *Data of the cables[16; 17]*

| **Cable type** | **AX50** | **AX95** | **AX150** |
|---|---|---|---|
| **$A_{wire}$ ($mm^2$)** | 50 | 95 | 150 |
| **$r_{DC\_wire}$ , 20°C (Ω/km)** | 0,641 | 0,320 | 0,206 |
| **$I_{max\_wire}$ (A)** | 150 | 220 | 290 |
| **$I_{max}$ (A)** | 300 | 440 | 580 |

The nominal output voltage level of the inverter will be probably set between 550-600 VAC as presented in chapter 4.2.2. Therefore, the maximum voltage drops for the calculation are selected from the corresponding values of the inverters' output voltages of 600 VAC, 575 VAC and 550 VAC, when $U_n$ is 900 VDC. Based on the equation (4.1) those are 26 VDC, 62 VDC, 99 VDC, or 2,9%, 6,9% and 11%.

Results calculated with the equations (5.9) and (5.11) are shown in the figures 5.1, 5.2 and 5.3. The curves present the power transfer capacity as a function of a DC cable's length. Thus, the curve shows the limit, below which the power transfer is possible. The linear part of the curves is due to the fact that the current is at its maximum limit and the calculation uses the equation (5.11) instead of the equation (5.9).

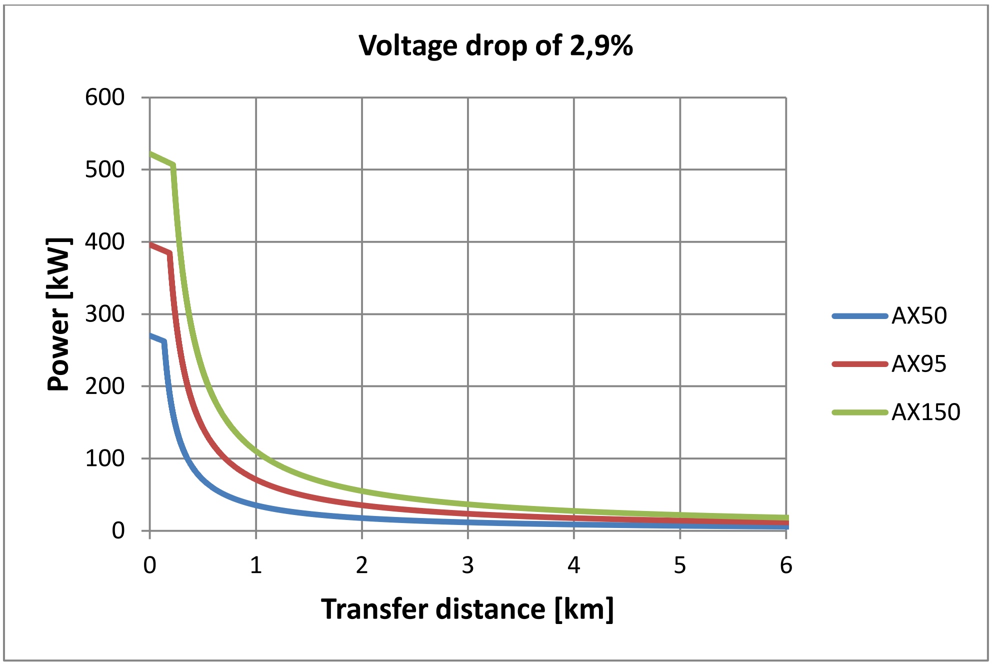


***Figure 5.1.*** *Power transfer capacity of the DC cables when the voltage drop limit is 2,9%.*

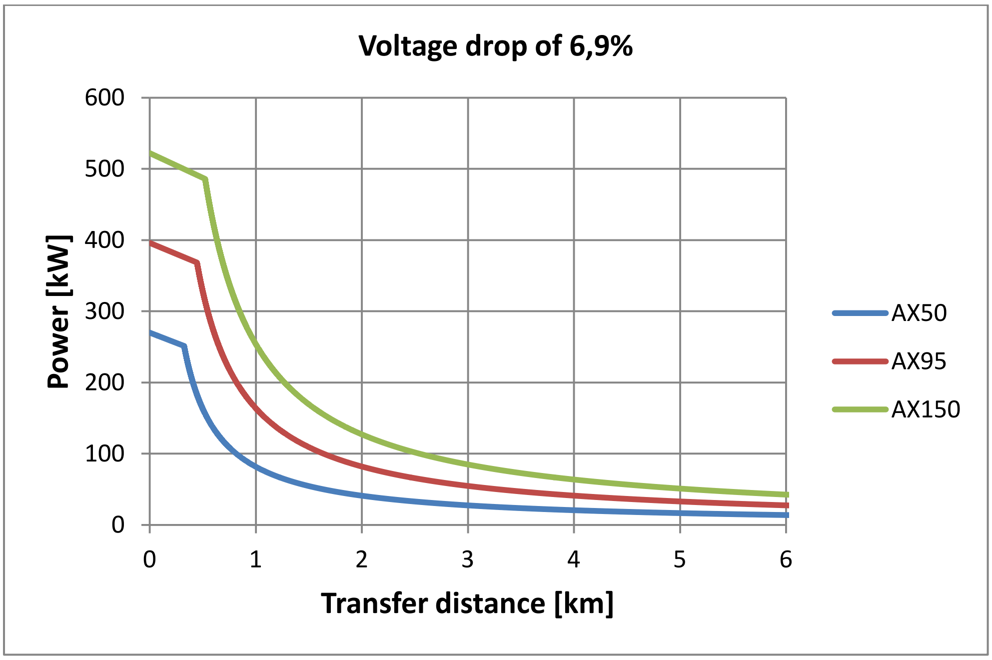


***Figure 5.2.*** *Power transfer capacity of the DC cables when the voltage drop limit is 6,9%.*

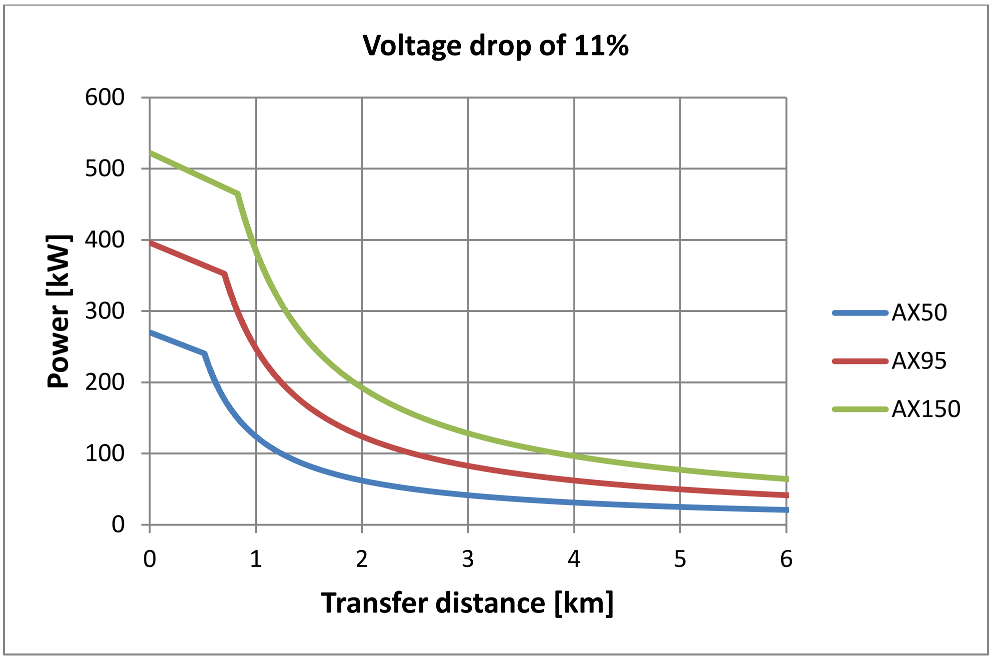


***Figure 5.3.*** *Power transfer capacity of the DC cables when the voltage drop limit is 11%.*

Besides the power transfer capacity, the figures 5.1-5.3 show how the dimensioning of the inverter affects the power transfer distance by affecting the voltage drop limit. With a voltage drop of 2,9 % a power of 100 kW can be transferred to the distance of 0,71 km using an AX95 cable. The transfer distance is increased to 1,63 km if a voltage drop of 6,9 % is used. Moreover, this transfer distance would be 2,48 km with voltage drop of 11 %, which is 3,5 times bigger than with the use of 2,9 % voltage drop.

# 6 POTENTIAL OF LVDC DISTRIBUTION IN THE VATTENFALL DISTRIBUTION AREA

In this chapter the scale at which the LVDC distribution can be utilized for substituting medium voltage branches in the Vattenfall distribution area in Finland is described. Based on the results of a mass computation of the network, the data of the branch lines with a single transformer can be listed. The branches which can be replaced by LVDC distribution, can be obtained by comparing the powers and branch lines' lengths to the limit curves in the figures 5.1-5.3.

## 6.1 Mass computation

The mass computation has been done with the Tekla NIS Network Information System for the entire distribution network of Vattenfall Verkko Oy. The mass computation performs, for example, a load flow calculation of the network and makes an updated list of network data. The program is not able to recognize individual parts of the medium voltage lines such as a branch line, so their data cannot be listed directly. However, sections of the medium voltage lines ending in a transformer can be found from the mass computation results. The data for the appropriate line sections and for the corresponding transformers can be listed. Thus, the analysis is limited to branch lines of a single transformer and tails of the multi-transformer branches, which are presented in the figure 6.1. These are locations where LVDC distribution would primarily be used.

"Branches", where the transformer is located directly below the main line or very close to it can also be found in the list of results from the mass computation. These are not sensible targets to LVDC distribution, and therefore branches less than 100 meter long are not included in the analysis. A 100 meter long branch is also quite a short line to be replaced by LVDC distribution. However, the existing medium voltage network topology, where a large number of branches are implemented linearly, needs to be considered. When this kind of branch line is rebuilt by cabling, the cable will be built along roads and fields, when possible. Therefore, ground cable can be a significantly longer than the currently used linear branch line.

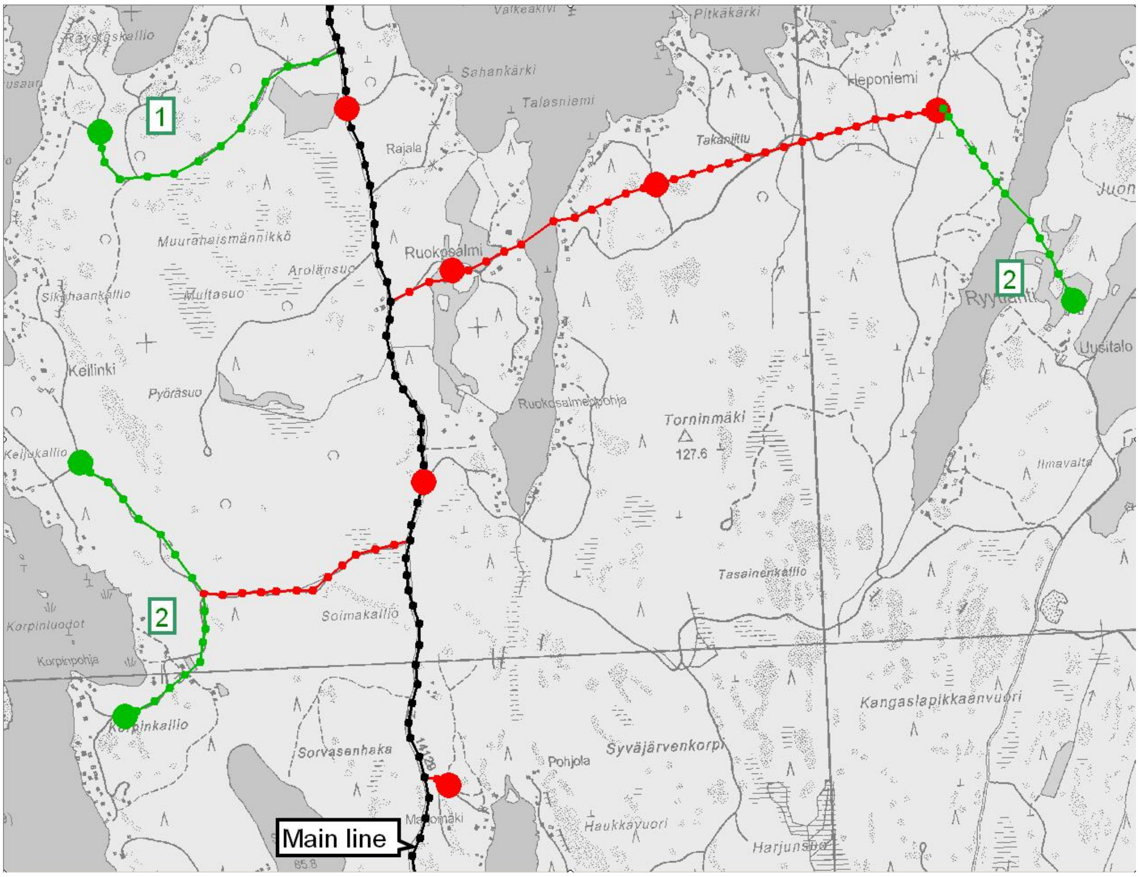


*Figure 6.1.* *Example case of processing mass computation results. Branch lines with a single transformer (number 1) and tails of the multi-transformer branches (number 2), which are colored green, are included in the analysis. Red colored parts of branches and transformers, which are less than 100 meter away from the main line, are not included in the analysis.*

Data from the mass computation can be listed, using the criteria mentioned above. Data from the list is summarized and presented in table 6.1. All data is related to sections of lines, which are longer than 100 meters and end in a transformer.

***Table 6.1.****Summarized data from results of mass computing.*

| | |
|---|---|
| **The total amount of sections (pcs)** | 8308 |
| **The total length of sections (km)** | 4809 |
| **The average length of sections (m)** | 579 |
| **The average age of transformers (a)** | 29 |
| **The average nominal power of transformers (kVA)** | 88 |
| **The total amount of aerial line in the sections (%)** | 99 |
| **The total amount of over 40 years old transformers (pcs)** | 1016 |

According to the table 6.1, the total length of sections for the analysis is 22 percent of the entire length of medium voltage network of Vattenfall Verkko Oy. The average age of a transformer is 29 years and more than 12 percent of transformers are over 40 years old, so a large part of the sections must rebuilt during the next ten years.

## 6.2 Network data processing

The existing distribution transformer has been dimensioned so that it is capable of supplying needed power also in maximum load situations. A large amount of branch lines are located in rural areas, where power consumption may have changed quite much since the time of dimensioning. This is due to the fact that the average age of transformers located in the end of branch lines is 29 years. Power consumption may have been dramatically decreased when farms have stopped operating or increased due to farms' increased power consumptions or new summer cottages. Therefore, some transformers are operating with very low load but some are at their maximum limit or even a little over during maximum load situations. Some transformers have also been changed to larger ones, due to the situation requiring so. However, the nominal power of the existing transformer can be used with good probability for evaluating the power, which the LVDC system has to be able to supply. Since the efficiency of the inverter is high, the assumption that the inverter is able to supply its entire input power can be used in this analysis. Thus, the following can be written:

$$S_n \approx P, \tag{6.1}$$

where $S_n$ is the nominal apparent power of transformer (VA) and P is input power of the inverter (W).

The total amount of line sections for the analysis is 8308 pieces, so under- and over-dimensioning of the individual power supply limits of the inverter compensate each other, so the overall results are fairly accurate estimate of the actual situation. Since the inverter requires a specific power P for its input, to be able to supply the needed power, the rectifier's output must be dimensioned larger by the amount of the transfer losses.

As was mentioned in chapter 6.1, when aerial lines are rebuilt using ground cable, the cable will almost always be longer than existing aerial line. This difference in length varies quite much between cases, since some branches are already built beside roads where a cable line will also be located, but some branches are built through the forest or some other route where the cable will not be built to. The average difference in length can be estimated to be 15 percent, so the lengths of line sections are multiplied by 1,15 for analysis.

## 6.3 Results of the analysis

The method for acquiring the sections' lengths and transfer power from the mass computation for the analysis, is described in chapter 6.2. Comparison of these values to the maximum limit curves of transfer capacity in chapter 5.2, determines whether it is possible to replace the section by LVDC distribution with the given maximum voltage drop value or not. The results of the analysis are summarized in tables 6.2 – 6.4, from which the number and length of replaceable sections can be found as well as their amount in percentage when compared to the amount of all analyzed sections.

***Table 6.2.*** *Data of line sections which can be replaced by LVDC distribution with a voltage drop of 2,9% across the cable.*

| **Voltage drop of 2,9%** | | | |
|---|---|---|---|
| **Cable type** | **AX50** | **AX95** | **AX150** |
| **The number of sections (pcs)** | 4270 | 6792 | 7717 |
| **The number compared to all sections (%)** | 51,4 | 81,7 | 92,9 |
| **The length of sections (km)** | 1695 | 3468 | 4216 |
| **The length compared to the length of all sections (%)** | 35,2 | 72,1 | 87,7 |

***Table 6.3.*** *Data of line sections which can be replaced by LVDC distribution with a voltage drop of 6,9% across the cable.*

| **Voltage drop of 6,9%** | | | |
|---|---|---|---|
| **Cable type** | **AX50** | **AX95** | **AX150** |
| **The number of sections (pcs)** | 6997 | 8045 | 8231 |
| **The number compared to all sections (%)** | 84,2 | 96,8 | 99,0 |
| **The length of sections (km)** | 3735 | 4579 | 4724 |
| **The length compared to the length of all sections (%)** | 77,7 | 95,2 | 98,2 |

***Table 6.4.*** *Data of line sections which can be replaced by LVDC distribution with a voltage drop of 11% across the cable.*

| **Voltage drop of 11%** | | | |
|---|---|---|---|
| **Cable type** | **AX50** | **AX95** | **AX150** |
| **The number of sections (pcs)** | 7607 | 8158 | 8256 |
| **The number compared to all sections (%)** | 91,5 | 98,2 | 99,4 |
| **The length of sections (km)** | 4315 | 4711 | 4767 |
| **The length compared to the length of all sections (%)** | 89,7 | 98,0 | 99,1 |

From the results can be noticed that even with a voltage drop of 2,9 % and using AX50 cable half of the line sections ending in a transformer can be replaced using LVDC distribution. However, percentage of the length of the sections is 16 percentage points lower, reflecting mainly the replaceability of short sections of lines. In all cases, the percentage of replaceable lines seems to be larger numerically than length, but the difference is more pronounced with low voltage drop limit because of the smaller power transfer capacity. However, most of the sections' length can be replaced even with a voltage drop of 2.9%, when using a cable of larger cross-sectional area. The results from the tables 6.2-6.4 are summarized in the figure 6.2.

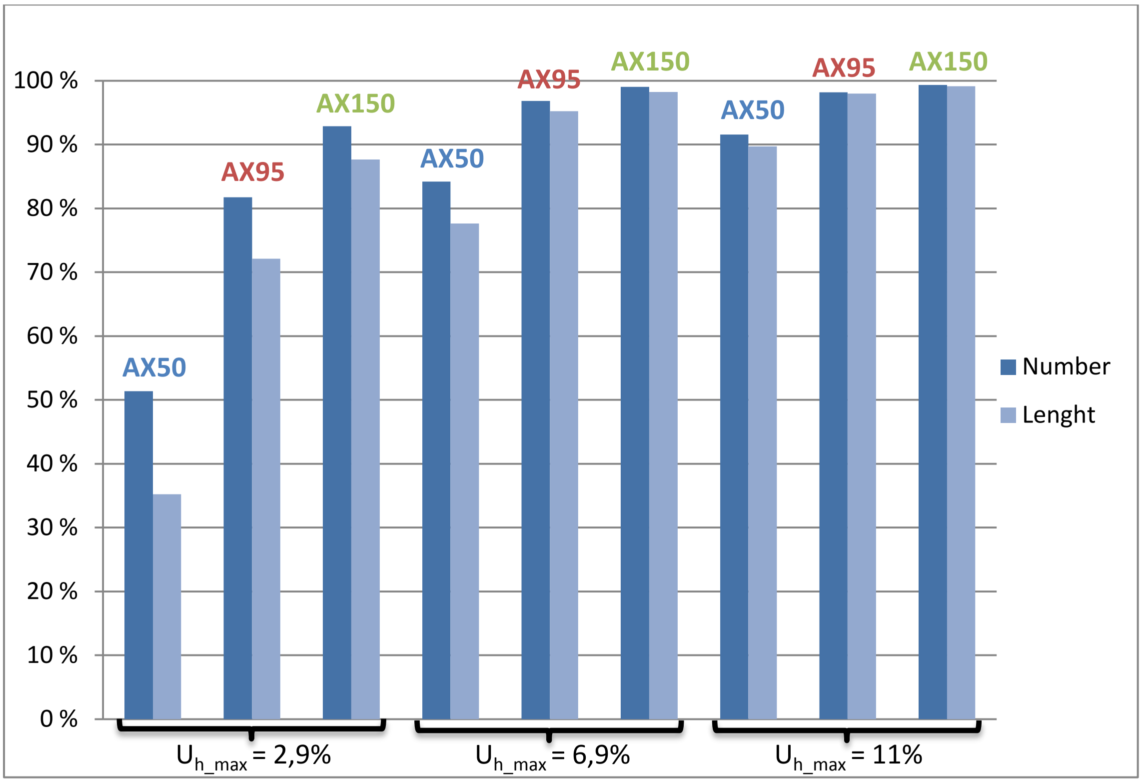


***Figure 6.2.*** *Summary of the results of the analysis. The figure shows the percentage of line sections replaceable by LVDC distribution in the distribution area of Vattenfall Verkko Oy.”Number” means the amount compared to amount of all sections and “Length” means the replaceable sections’ length compared to length of all sections. The cable types are presented above and the voltage drop limits below the bars.*

Based on this analysis, the use of a voltage drop limit of 6,9% seems to be the most techno-economically sensible alternative of the three options. In that case, power transfer capacity of AX50 cable is enough to replace most of the line sections, and thus cable costs can be kept low. Furthermore, the inverter does not have to be dimensioned to have as high short-circuit current supply capability as with higher limits of voltage drop.

A large part of the sections must rebuilt in the near future because of ageing. Based on the results of analysis, LVDC distribution is a usable solution for rebuilding branch lines with a single transformer and its power transfer capacity is high enough. Depending on voltage drop selection, in the distribution area of Vattenfall Verkko Oy there are 4216-4767 km line sections, which can be replaced by LVDC distribution by a technical point of view. This is 19-22 percent of the entire length of medium voltage network of Vattenfall Verkko Oy.

It seems to be also technically possible to replace short and low power multi-transformer branch lines with LVDC distribution, based on figures 5.1-5.3 and figure 6.2. Then the structure resembles the one in figure 4.3 with customer-end inverter, because the rectifier would be at the beginning of the branch and the inverters would take the transformers’ place. In this case, however, it must be taken into account that transferred power is divided to several line sections, and that the multi-transformer branch supplies a larger area than a branch with a single transformer. Therefore, must be left more power transfer reserve for new inverters, if those are needed during the operating life of the distribution system. Thus, in multi-transformer branches more heavy-gauge gables and probably also higher voltage drop than 6,9% would have to be used, so that the power transfer capacity would be sufficient. Moreover, cable dimensioning and calculation of sufficient transfer capacity must be done case-specific, but the calculation methods and curves in chapter 5 can also be utilized for designing multi-transformer branch lines.

When beginning large scale utilization of LVDC distribution, it would be useful to decide exactly what kind of branches it would replace and how big power transfer capacity is wanted. Thus, one maximum limit of voltage drop could be chosen, so then the nominal values of the inverter as well as Dyn-transformer could be kept constant. Therefore, the number of new types of components in the network can be kept as low as possible, which makes their maintenance and replacement easier.

Especially, if a decision is made to replace the multi-transformer branch lines with LVDC distribution and the low voltage AC network is also in poor condition, or a completely new low voltage network will be built, a system with customer-end inverters should also be considered. With that solution the power transfer capacity can be improved and the losses reduced, since the lower distribution voltage of 400VAC is not used for power transfer at all.

# 7 CONCLUSIONS

The LVDC distribution system enables easy connecting point for distributed generation and energy storages. The amount of which will increase in the future and develop the network towards a smart grid. According to the experiences of previous tests, the LVDC system improves power quality and tolerates medium voltage network autorecloses without voltage drops or supply interruptions. Also reliability of medium voltage network improves, since the LVDC system forms its own protection area.

The analysis indicates, that depending cable type and voltage drop limit, 51-99 % of branch lines with a single transformer and tails of the multi-transformer branches are replaceable using LVDC distribution in the distribution area of Vattenfall Verkko Oy. Moreover, using AX150 cable can be replaced 4216-4767 km line sections by LVDC, which is 19-22 percent of the entire length of medium voltage network of Vattenfall Verkko Oy. Moreover, it seems to be that the transfer capacity of LVDC distribution is also sufficient for replacement of short and low-power multi-transformer branches. Thus, it can be inferred that LVDC distribution has a good utilization potential.

Based on the analysis, the use of a voltage drop limit of 6,9% seems to be the most techno-economically sensible alternative of the three options (2,9%; 6,9% or 11%). In that case, power transfer capacity of AX50 cable is enough to replace most of the branch lines with a single transformer, and thus cable costs can be kept low.

The calculations of this thesis have been done to transfer voltage of 900VDC, because it is the maximum DC voltage with unipolar connection due to the cable standards. When beginning large scale utilization of LVDC distribution, it would be useful to develop a cable specifically for LVDC power transfer, which would allow the use of maximum low voltage of 1500VDC with unipolar connection. This would improve power transfer capacity of the system, reduces losses and would increase the utilization potential of LVDC distribution.

A large part of the branches, as well as the entire medium voltage network, need to be rebuilt in the near future. Based on the analysis, LVDC distribution is in a technical point of view the one potential solution for this rebuilding. The price of power electronics and the maintenance costs of the system are determined the economic profitability of LVDC distribution, and so are the biggest influencing factors for the implementation. These subjects are considered in the Master’s thesis of Viivi Naakka, titled Reliability and Economy Analysis of the LVDC Distribution System, which will be completed in early 2012. However, power electronics are constantly evolving, so the price will be reduced in the future. Second LVDC test site will be implemented in the cooperation of

Vattenfall Verkko Oy and ABB Oy Drives in 2012, from which the knowledge about the need for maintenance and its costs as well will likely get more accuracy.

# REFERENCES

[1] Salonen, P. Tasasähkön hyödyntämismahdollisuudet sähkönjakelussa. Master's thesis. Lappeenranta 2006. Lappeenranta University of Technology. 86 p. http://www.lut.fi/fi/technology/lutenergy/electrical_engineering/research/electricitymarkets/publications/Documents/Diplomity%C3%B6t/Diplomityo_Pasi_Salonen.pdf

[2] Voutilainen, V. Tasasähkönjakelun käyttöpotentiaalin määrittäminen. Master's thesis. Lemi 2007. Lappeenranta University of Technology. 117 p. https://www.doria.fi/bitstream/handle/10024/32997/nbnfi-fe20072145.pdf?sequence=1

[3] Vattenfall Verkko Pohjola Verkko Suomi 2011. Unpublished slideshow. 2011. Vattenfall Verkko Oy.

[4] Lakervi, E., Partanen, J. Sähkönjakelutekniikka. Helsinki 2008, Otatieto. 294 p. ISBN 978-951-672-357-3

[5] Energiamarkkinavirasto. Sähkömarkkinalaki 386/1995. 1995. 18 p. http://www.energiamarkkinavirasto.fi/files/sahkomarkkinalaki_386-1995.pdf

[6] Partanen, J., Pyrhönen, J., Silventoinen, P., Niemelä, M., Lassila, J., Kaipia, T., Salonen, P., Peltoniemi, P., Nuutinen, P., Lana, A., Haakana, J., Pinomaa, A., Makkonen, H., Voutilainen, V., Paajanen, P., Järventausta, P., Tuusa, H., Suntio, T., Kannus, K., Lahti, K., Nikander, A., Mäkinen, A., Alahuhtala, J., Suntila, T., Nousiainen, L., Rekola, J., Vornanen, T. Tehoelektroniikka sähkönjakelussa – Pienjännitteinen tasasähkönjakelu. Lappeenranta 2010. LUT Energia tutkimusraportteja 5. 170 p.
ISBN 978-952-214-981-7
http://www.lut.fi/fi/technology/lutenergy/electrical_engineering/research/electricitymarkets/publications/Documents/Tehoelektroniikka_sahkonjakelussa-Loppuraportti-2010_ISBN978-952-214-981-7.pdf

[7] Rekola, J. Kolmitasoiset suuntaajat tasasähkönjakelussa. Master's thesis. Tampere 2009. Tampere University of Technology. 82 p. http://webhotel2.tut.fi/units/set/opetus/pdf%20julkiset%20dtyot/Rekola_Jenni_julk.pdf

[8] Kylkisalo, T., Alanen, R. Tasajännite taajaman sähkönjakelussa ja mikroverkoissa. 2007. VTT Working Papers 78. 135 p.
ISBN 978-951-38-6629-7
http://www.vtt.fi/inf/pdf/workingpapers/2007/W78.pdf

[9] Partasen, J., Pyrhönen, J., Silventoinen, P., Niemelä, M., Lindh, T.,Kaipia, T., Salonen, P., Nuutinen, P., Peltoniemi, P., Lassila, J. Tasasähköjakelujärjestelmän toiminnalliset kriteerit ja sähköturvallisuustarkastelu. Lappeenranta 2007. Lappeenranta University of Technology. 77 p.
http://www.lut.fi/fi/technology/lutenergy/electrical_engineering/research/electricitymar-kets/publications/Documents/Tasasasahkojarjestelman_toiminnalliset_kriteerit_ja_sahkoturvallisuus-1.pdf

[10] Lähdeaho, T. DC-distribution. Unpublished slideshow. 2009. Vattenfall Verkko Oy.

[11] Niiranen, J., Komsi, R., Routimo, M., Lähdeaho, T., Antila, S. Experiences from a Back-to-Back Converter fed Village Microgrid. 2010. 5 p.
http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5638991

[12] Partanen, J., Pyrhönen, J., Silventoinen, P., Niemelä, M., Lindh, T., Kaipia, T., Salonen, P., Nuutinen, P., Peltoniemi, P., Lassila, J. Tehoelektroniikka sähkönjakelussa Hankeosio 1/2. Lappeenranta 2008. Lappeenranta University of Technology. 94 p.
http://www.lut.fi/fi/technology/lutenergy/electrical_engineering/research/electricitymarkets/publications/Documents/Tehoelektroniikka_sahkonjakelussa-Raportti_osa1-2008.pdf

[13] Vornanen, T. Tehoelektroniikkaa sisältävien sähkönjakeluverkkojen simulointi PSCAD-ympäristössä. Master’s thesis. Tampere 2009. Tampere University of Technology. 86 p.
http://webhotel2.tut.fi/units/set/opetus/pdf%20julkiset%20dtyot/Vornanen_Tuomo_julk.pdf

[14] Pienjänniteverkon suunnitteluohjeet. Unpublished document. 2011. Vattenfall Verkko Oy.

[15] Interview 9.11.2011. Komsi, R. ABB Oy Drives.

[16] Tekla NIS. Network Information System. Referred 10.10.2011.

[17] Voimakaapelit AXMK 0,6/1 kV alumiini. 2011. Draka. Referred 10.10.2011. http://www.draka.fi/draka/Countries/Draka_Finland/Languages/suomi/navigaatio/Tuotteet/Kiinteistoverkot/Voimakaapelit/Voimakaap._1kV_Al/AXMK_4xA_1_kV_JT_D1631.pdf