Open your mind. LUT.
Lappeenranta University of Technology

FACULTY OF TECHNOLOGY
LUT ENERGY
ELECTRICAL ENGINEERING

MASTER'S THESIS

OPTIMIZATION OF THE POWER CABLE FOR LOW VOLTAGE DIRECT CURRENT DISTRIBUTION SYSTEM

Examiners Prof. Jero Ahola
Prof. Igor Ryazanov

Author Yuliya Khegay

Abstract

Lappeenranta University of Technology
Faculty of Technology
Electrical Engineering

Yuliya Khegay

Optimization of the power cable for low voltage direct current system

Master's thesis
2010
83 pages, 40 pictures, 6 tables, and 1 appendix

Examiners: Professor Jero Ahola and Professor Igor Ryazanov

Keywords: LVDC, PLC, power cable, power loss, voltage drop, frequency dependence

The demand for electricity is constantly growing in contemporary world and, in the same time, quality and reliability requirements are becoming more rigid. In addition, renewable sources of energy have been widely introduced for power generation, and they create specific challenges for the network. Consequently, new solution for distribution system is required, and Low Voltage Direct Current (LVDC) system is the proposed one.

This thesis focuses on the investigation of specific cable features for low voltage direct current (LVDC) distribution system. The LVDC system is public ±750 VDC distribution system, which is currently being developed at Lappeenranta University of Technology. The aspects, considered in the thesis, are reliable and economic power transmission in distribution networks and possible power line communication in the LVDC cable.

Acknowledgments

I would like to thank people, who contributed into this work.

Firstly, I would like to thank my supervisor Tero Kaipia, my professors Jero Ahola and Igor Ryazanov for their great help and useful advice. Also I want to thank Andrey Lana, Pasi Salonen, Antti Kosonen, Antti Pinomaa and other people from Electrical Engineering Department for their co-operation. In addition, I want to thank my professors and lecturers at MPEI and LUT for the useful knowledge that they gave to me.

Secondly, I want to thank project manager Julia Vauterin and Sergey Shirinskiy for the establishing double-degree program for MPEI students and its development.

Thirdly, I warmly thank my family, my dear parents and brothers for their support and love.

Fourthly, I am very grateful to my dear friends: Daniil Lenevskiy for his help and support; Natalia Kabalina; Yury Chistyakov; Nikita Lovinskiy; Alexander Gorobets; Liliya Ikhsanova for being my perfect flatmate, and all awesome students from Electrical Engineering. Special thanks to people, who supported me, during my extended stay in London, caused by volcano eruption in Iceland.

Lappeenranta, May 2010
Yuliya Khegay

Table of contents

Abbreviations and symbols

Abbreviations

AC	Alternating Current
ARQ	Automatic Repeat Request
CENELEC	European Committee for Electrotechnical Standardization
DC	Direct Current
FFT	Fast Fourier Transform
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
LVDC	Low Voltage Direct Current
OFDM	Orthogonal Frequency Division Multiplexing
PE	Polyethylene
PLC	Power Line Communications
PVC	Polyvinyl Chloride
PWM	Pulse Width Modulation
TEM	Transverse Electromagnetic
VAC	Volts Alternating Current
VDC	Volts Direct Current
XLPE	Cross-Linked Polyethylene

Symbols

A_g	air-gap distance
b_h	height of the sector
C	capacitance
C	cost
c_{loss}	cost of losses
d	conductor diameter
G	conductivity
f	frequency
h_{ins}	insulation thickness
I	current
i	peak value of current
I_k	short-circuit current
k	coefficient, defined by type of the conductor
L	inductance
L_{ex}	external inductance
P	active power
p	interest rate
R	resistance
r	resistance
r	load growth
T	temperature
t	time
U	voltage
u	peak value of voltage
S	apparent power
s	distance between the centers of the conductors
X	reactance
x	distance from the beginning of the line
y	coefficient for proximity and skin effect
Z	impedance

Z_c	characteristic impedance

Subindeces

ac	alternating current
avg	average
cons	construction
d	diagonal
dc	direct current
dc2	value for two poles of bipolar direct current system
LL	line-to-line
loss	losses
n	nominal
p	proximity effect
oc	open-circuit
s	skin-effect
sc	short-circuit

Greek letters

Δ	difference
α	attenuation coefficient
β	propagation coefficient
γ	propagation constant
δ	dielectric loss angle
ε	permittivity
μ	permeability
κ	propagation parameter
κ	capitalization factor
ν	propagation velocity
ω	angle frequency

1 Introduction

The demand for electricity is constantly growing in contemporary world and, in the same time, quality and reliability requirements become more rigid. In addition, renewable sources of energy have been widely introduced for power generation, and they create specific challenges for the network. Therefore, new distribution system structure is required, and Low Voltage Direct Current (LVDC) system was proposed at Nordic Distribution Automation Conference (Kaipia et al., 2006).

The thesis contains description of the LVDC and analysis the cable properties for it. This chapter includes the thesis scope and objectives.

1.1 Scope

This thesis focuses on the investigation of cable for low voltage direct current (LVDC) distribution system. The LVDC system is public ±750 VDC distribution system, which is currently being developed at Lappeenranta University of Technology. The thesis considers specific features of the LV cable structure, which are mainly determined by two cable applications: reliable, high quality and economically feasible power transmission and high frequency power line communication. During the investigation, both technical and economical factors, determining the cable selection, are discussed.

1.2 Objectives

The conventional distribution system is 3-phase AC system. Consequently, the existing AC cables have parameters and structure optimized for AC-use. This work considers the special features and parameters of LVDC system and their influence on the cable. Consequently, the objectives of the work are listed below.

- Definition of requirements set by operating environment on power cable properties:

- ✓ the applications: power transmission and power line communication;
- ✓ power transmission:
  - voltage level and overvoltages
  - overcurrents
  - power losses and voltage drop
  - electromagnetic interferences
  - frequency dependences of cable parameters
  - costs analysis
- ✓ power line communication
  - high-frequency losses
  - characteristic impedance
  - signal attenuation

- Investigation of the properties of underground cable network installation techniques and accessories.
- Definition of demands for cable development and recommendations for cable structure.

The second chapter of the work considers background and main parts of LVDC system. The third chapter introduces PLC technology and special requirements for cable, set by high frequency signal transmission. The fourth chapter analyses from power distribution point of view: operating conditions, fault situations, cable modelling, and performance of existing AC cables in LVDC. The fifth chapter summarizes all the requirements and gives recommendations for cable selection. Finally, the cable is proposed, which is most suitable for DC power transmission and PLC applications.

2 Low voltage direct current distribution

Traditionally, three-phase AC system is employed for electricity distribution in Europe. Nowadays, the research, fulfilled by Lappeenranta University of Technology, shows the feasibility of LVDC system for certain applications and its impacts on reliability of power delivery.

This chapter provides brief description of proposed LVDC system, its equipment structure, and, in addition, main concepts of existing high voltage (HV) direct current system.

2.1 LVDC system background

The conventional public electricity distribution system in Finland is the two voltage level 20/0.4 kV AC distribution system. Furthermore, for some applications the three voltage level 20/1/0.4 kV system has proved to be more suitable and economically reasonable compared with the above mentioned traditional one (Lakervi and Partanen, 2008). Low voltage direct current system is an alternative for 20/0.4 kV and 20/1/0.4 kV AC distribution systems. The public LVDC system was proposed by the researchers of Lappeenranta University of Technology. The first LUT publication concerning this system was in 2006 in NORDAC conference (Kaipia et al., 2006). Different types of system configuration, parameters, and components were considered. Finally, bipolar IT system with rated voltage of ±750 V was proposed as the most technically and economically suitable solution.

The DC network gives reasonable economical effect: the losses in the cables are reduced significantly, the use of cable core metal is more effective, and the power capacity is increased compared with conventional 20/0.4 kV system. Besides that, the quality of electrical energy supply increases: customer-end inverters can maintain stable amplitude and frequency of the customers’ voltage regardless of supply. In addition, the possibility of uninterruptible reliable supply and non-dependability from the grid, because of the specific system structure and possible integration of renewable energy sources (Kaipia, 2009).

Similar solutions have been studied by research groups in other countries also. For instance, the investigation of low voltage direct current distribution system was fulfilled in Italy. The voltage level of the proposed system was 800 VDC or ±400 VDC. Their investigation has proved that if three- conductor system (positive pole, negative pole, and neutral pole) is used, then the transmitted power capacity exceeds AC system power capacity by 30% (Borioli, 2004). In case of using 3-wired cable instead of 4-wired increase the economical savings achieved with DC-system considerably. The ±400 VDC system, with four conductor cable has transmission power capacity, which two times exceeds AC system capacity (Borioli, 2004).

Researchers from Chalmers University of Technology in Sweden investigated the efficiency of LVDC (Nilsson and Sannino, 2004). They concluded that the efficiency of using transformers in this case is higher than for AC distribution. In addition, if DC is applied in both LV and MV levels, the efficiency of DC system exceeds the efficiency of AC system.

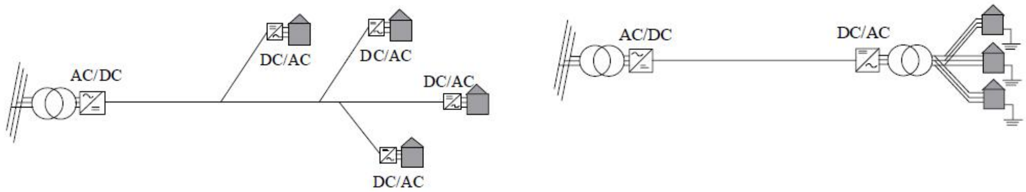
There was a research in the University of the Ryukyus, Japan; and Sungkyunkwan University, Korea, about DC distribution system on an island (Kurohane, 2009). The control system was proposed for wind turbine generator: it makes the output of generator smooth at low speeds and helps to get the maximum output, when the wind speed varies. Besides that, the battery is used to improve the system operation in fault situations. The study proved the reliability of DC distribution system with windmill, when control is performed according to the proposed control schemes.

The investigation in North Carolina State University, USA, concerns shipboard distribution system. The simulated prototype research presented solution for the problem of interaction of power converters in the system and also proposals for the control of the system and required filtering. In addition, the design of grounding system is also investigated (Baran and Mahajan, 2003).

The researchers from University of Tennessee and Oak Ridge National Laboratory compared the features of AC and DC distribution systems (Starke, 2008). The high losses in AC system with DC sources and loads were implied. If AC system is supplied by AC source, DC system by DC source and the loads are 50% DC and 50% AC then the efficiency of AC and DC systems are equal. If AC system has DC source then further losses are introduced. As a conclusion, the authors propose to give both AC and DC supply to every load. However, the problem of DC system is low efficiency of DC-DC conversion.

2.1.1 LVDC system concept

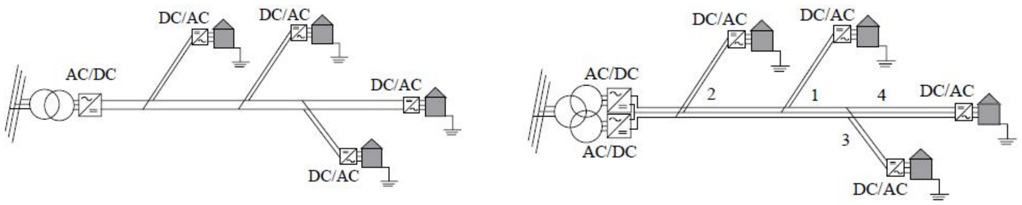
The direct current low voltage (LVDC) system replaces traditional low voltage AC distribution system and parts of medium voltage system. LVDC can have different topologies. The Figure 2.1a shows one possible solution, when LVDC completely replaces the local LV network. The DC/AC conversion happens before the energy is supplied to the customer. The Figure 2.1b depicts the other possible solution, namely, LVDC link: after DC/AC conversion the transformer changes the level of voltage. The first solution is preferable, because it does not increase the number of transformers in the system.



a) b)

Fig.2.1. Topology of system using LVDC (Salonen et al. 2008): a) – DC/AC conversion in each customer, b) – DC/AC conversion followed by transfomer

There are two possible system constructions: unipolar and bipolar system. The unipolar system has two wires and it provides only one level of voltage: 1500 V DC. The Figure 2.2a) shows the topology of unipolar LVDC system.



a) b)

Fig.2.2. The possible configurations of LVDC system: a) – unipolar; b) – bipolar. (Salonen et al., 2008a)

Bipolar configuration admits three different voltage levels: +750 V, -750 V, and 1500 V. The possible load connections are shown in the Figure 2.2.b). The load can be connected: 1 – between positive pole and neutral, 2 – between negative pole and neutral, 3 – between positive and negative pole, 4 – between positive and negative pole with neutral connection (Salonen et al., 2008a). Mainly, the first and second types of the connections are used, as thy enable use of lower voltage converters than cases 3 and 4, and thus reduce the price of converters. In these cases the voltage is ±750 VDC.

Different configurations of LVDC system were investigated and, finally, the following system structure was proposed (Salonen et al., 2008a; Salonen et al., 2009):

- Bipolar LVDC ±750 VDC
- Customers connected mainly between single pole and neutral
- Unearthed IT system due to safety issues during earth fault situations
- Power line communication technology is implemented and used in protection and operation
- Protection system includes both traditional relaying and functions integrated in converters

- Applied mainly in the rural networks, when certain line length and power demand make the LVDC economically feasible.
- Special applications exist also in city and individual environments, like lightning

The Figure 2.3 shows main structure of LVDC system

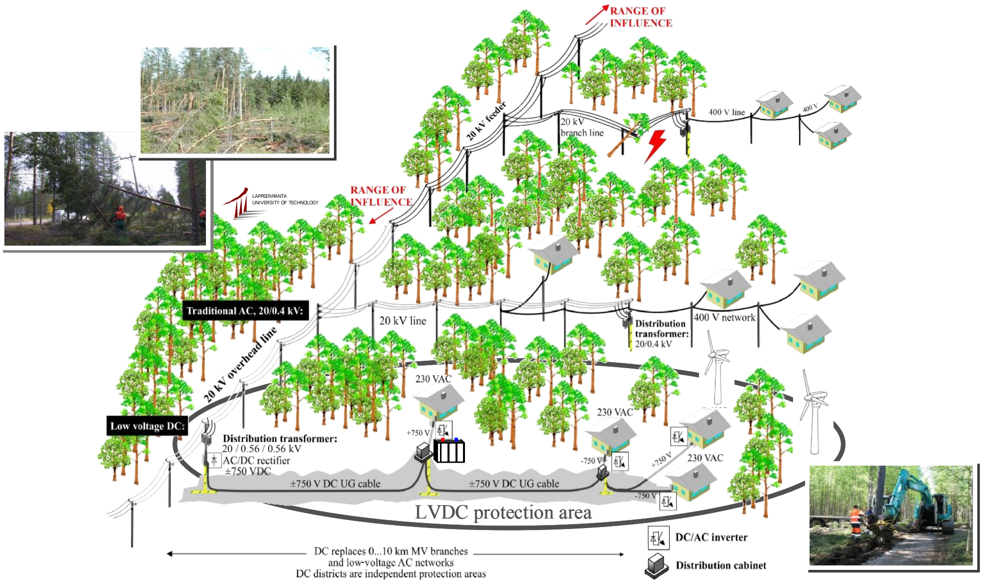


Figure 2.3. Structure of LVDC system (Partanen et al., 2010)

It is worth to mention the study of economically feasible range for LVDC. During the research fulfilled at LUT (Kaipia, 2009), the building and operating costs for LVDC system were considered and investigated. As a result, the recommendations for LVDC use were given, depending on peak power and line length. The Figure 2.4 depicts recommendations, where the upper limit for the applicability of LVDC is set by 10% voltage drop in power line and the lower limit is set by economical calculations.

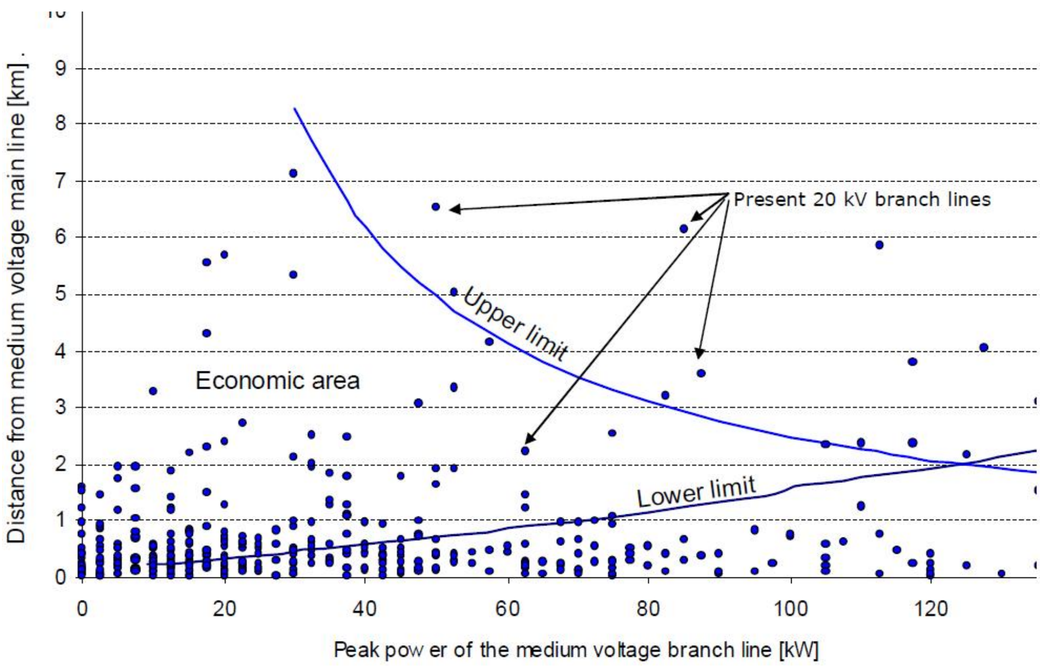


Fig.2.4. The economically feasible range for LVDC application (Lassila et al., 2008).

2.1.2 The existing HV lines and cables

There has been a lot of projects concerning HVDC transmission lines, starting from the demonstration 2 kV DC line in Germany from Miesbach to Munich in 1882 (Arrillaga, 1998). The cable construction evolved from oil-impregnated cables to cables with polymeric insulation. However, space charge phenomena inhibited the exploitation of polymeric insulation in DC cables. This issue was eliminated recently by using modified PE composition (Maruyama et al., 2004; Borealis, 2008).

One of the leading companies of HVDC technology, ABB, has constructed a number of HVDC projects in different countries: Finland, Canada, China, and other countries. The technology developed by ABB is HVDC Light® (ABB, 2008). The converters in the system are based on insulated gate bipolar transistors (IGBTs). The Figure 2.5 shows main components of the system.

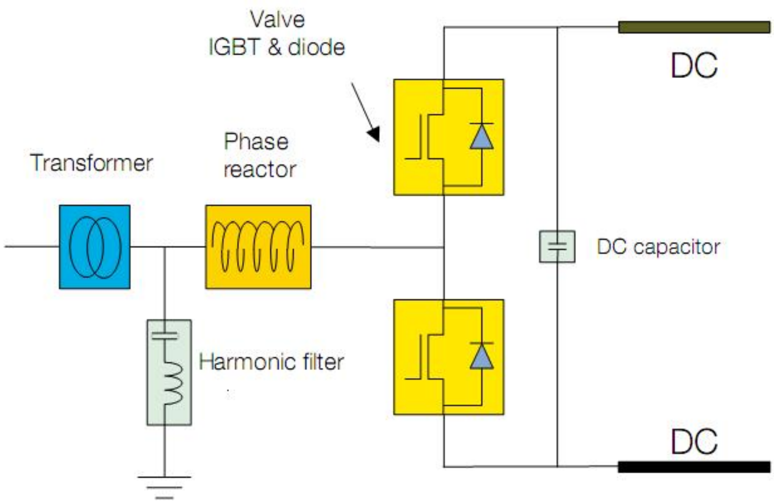


Fig.2.5. Single-line diagram for HVDC Light® line (ABB, 2008)

ABB designed cables for the DC application: land cables and submarine cables. The Figure 2.6 shows the components of underground HVDC cable. The round conductor is produced of copper or aluminium wires. It also may contain special tape for preventing water distribution on the length of the cable in case of cable injury (ABB, 2008).

Fig.2.6. HVDC Light® cables by ABB

The insulation of HVDC consists of several layers. Firstly, there is a semi-conducting screen on the surface of the conductor. The screen is fabricated from semi-conductive polyethylene. The main insulation of the cable on the top of previously mentioned layer is fabricated from specially modified cross-linked polyethylene (XLPE). The insulation is also covered by semi-conductive layer. Then follows the copper-wire screen. The outer sheath consists of thermoplastic polyethylene or PVC. PE has higher mechanical properties and PE is applied in most cases. PVC is halogen-containing material, but it is flame-retardant.

The reason for application specially modified XLPE is the space charge issue. The electro-magnetic field in the cable in typical applications is between 10-15 kV/mm. According to the analysis done at Tampere University of Technology, in the LVDC system the electromagnetic fields are low and space charges do not cause problems (Suntila, 2009). In addition, the semi-conductive layers, used in HVDC due to the high-voltage application to make the electromagnetic field even, are not required in the LVDC case.

This cable was designed especially for high-voltage DC applications. In case of LVDC application the situation is different and the electromagnetic fields are much weaker.

2.2 LVDC equipment structure

The LVDC system transmits electric energy from distribution transformer to the customer. It includes power line communication for both system and external purposes. The special features of LVDC require special equipment, such as converters, different types of protection equipment, and PLC equipment.

2.2.1 Converters

The converters are placed in the supply end of LVDC line and in the customer end of LVDC line. One of the options for source-end converter in LVDC system is three-phase, full bridge rectifier, shown in Figure 2.7.

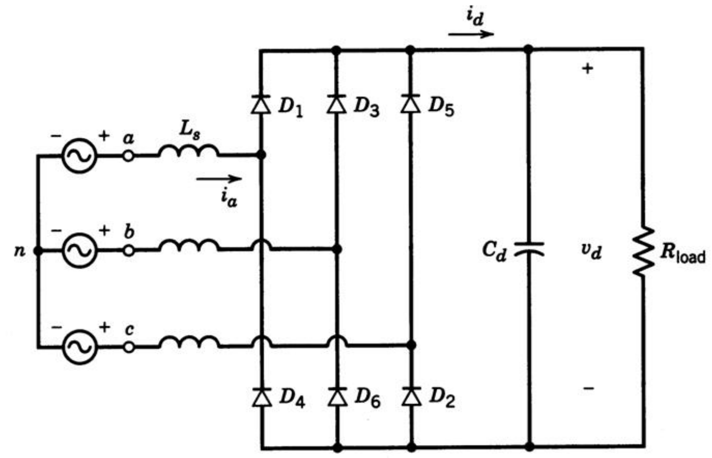


Fig.2.7. Three-phase, full-bridge rectifier (Mohan, 2003).

If the simplified circuit for the rectifier is considered the waveforms, which are shown in Figure 2.3, are obtained.

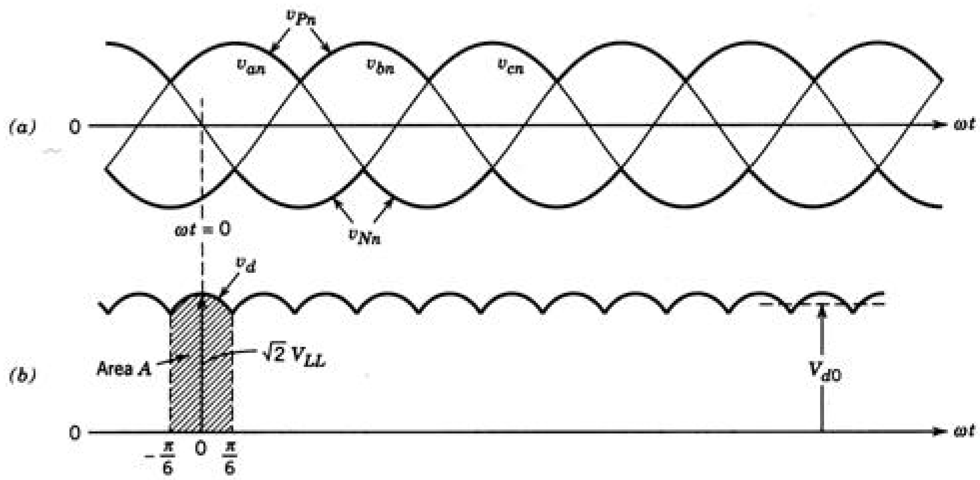


Fig.2.8. Waveforms in the circuit (Mohan, 2003)

When the six-pulse rectifier is considered the average value of output voltage can be calculated by integration and on the π/3 interval according to the equation (2.1).

$$U_{do} = \frac{3}{\pi}\int_{-\pi/6}^{\pi/6} \sqrt{2}\, U_{LL} \cos(\omega t)\, d\omega t = 1.35 U_{LL} \qquad (2.1)$$

The other option of rectifying AC current is to use six-pulse thyristor rectifier in Figure 2.9.

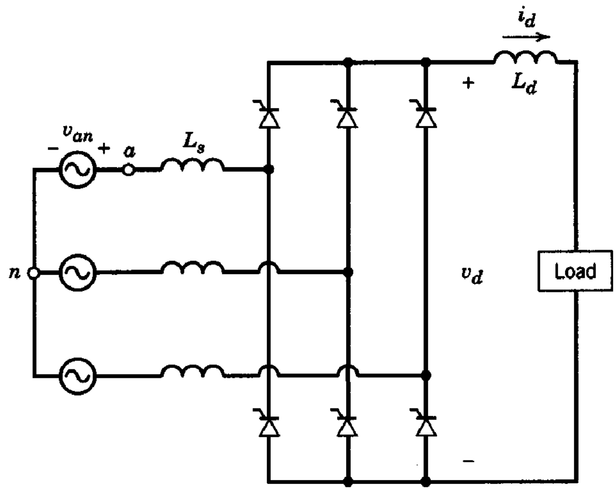
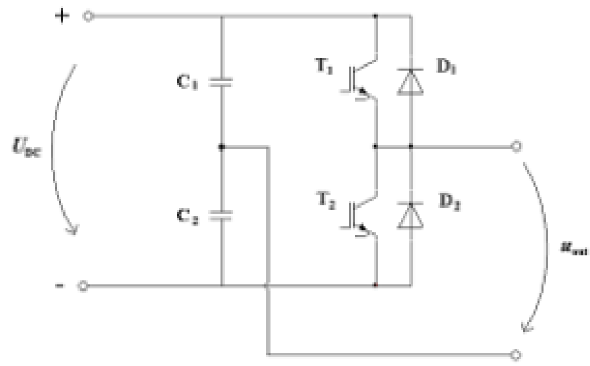


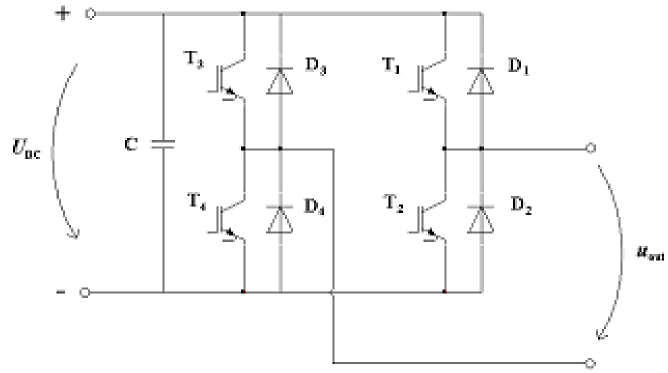
Fig.2.9. Six-pulse thyristor rectifier (Mohan, 2003)

The same value of output voltage can be obtained for thyristor rectifier, as for diode rectifier. Actually, 12-pulse thyristor rectifier, composed of two 6-pulse thyristor rectifiers, is used in LVDC system.

Customer-end inverters can have different topology: half-bridge and full-bridge. The Figure 2.10 depicts both topologies. Half-bridge inverter is easier to control and has lower costs compared to full-bridge inverter. In order to produce 230 VAC output, it needs minimum of 650 VDC input. On the other hand, the full-bridge inverter allows higher level of input voltage than half-bridge inverter.



a)



b)

Fig.2.10. Single-phase inverters: a) – half-bridge topology, b) – full-bridge topology (Nuutinen et al., 2008)

However, in half-bridge topology capacitors C_1 and C_2 are required, which have large physical size for low-frequency applications and short lifetime (Nuutinen et al., 2008). In addition, the capacitances of C_1 and C_2 are not equal, so it makes the control of inverter more complicated. As a result, half-bridge topology is not applicable for LVDC system, and full-bridge topology is used because it eliminates the demand for capacitors (Nuutinen et al., 2008).

2.2.2 *Protection*

LVDC system structure differs from conventional distribution system; consequently, the protection equipment is different. In addition, the system has IT configuration, which also sets certain requirements: ground fault is not turned into short circuit fault and DC insulation monitoring device is used.

The LVDC system requires the following types of protection (Salonen et al., 2009):

- Over-current protection
- Short-circuit protection
- Earth fault protection

As far as equipment for protection is concerned, the following protection devices are used in LVDC (Salonen et al., 2009):

- molded case circuit breaker
- DC fuses
- insulation monitor

The molded case circuit breaker, composed of circuit breaker and over-current relay, is used for short circuit protection. The molded case circuit breaker can be situated on DC or on AC side of the converter. If used on AC side, it can also protect against switch faults in the converter. The other device, used for protection is DC fuse.

As the LVDC is ungrounded system, short-circuit protection cannot be used also for earth fault protection, which should be treated separately. For these purposes insulation monitor is employed. The protection scheme is depicted in Figure 2.11.

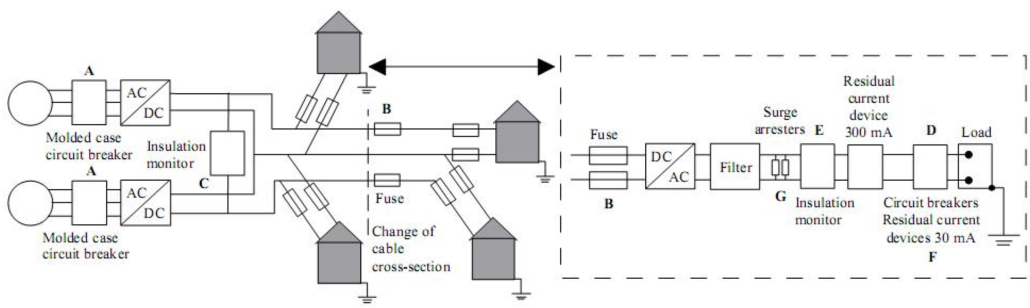


Fig.2.11. The protection scheme for IT LVDC system (Salonen et al., 2009)

For customer AC network, circuit breakers and fuses are employed for short-circuit protection. For earth fault protection, the customer needs insulation monitoring devices. For human safety 30 mA residual current devices are employed.

2.2.3 Communication system

The low voltage distribution network can be used as communication medium for PLC application. The technology and components, which are used for PLC in LVDC is similar to the technology for motor power cable (Ahola, 2003).

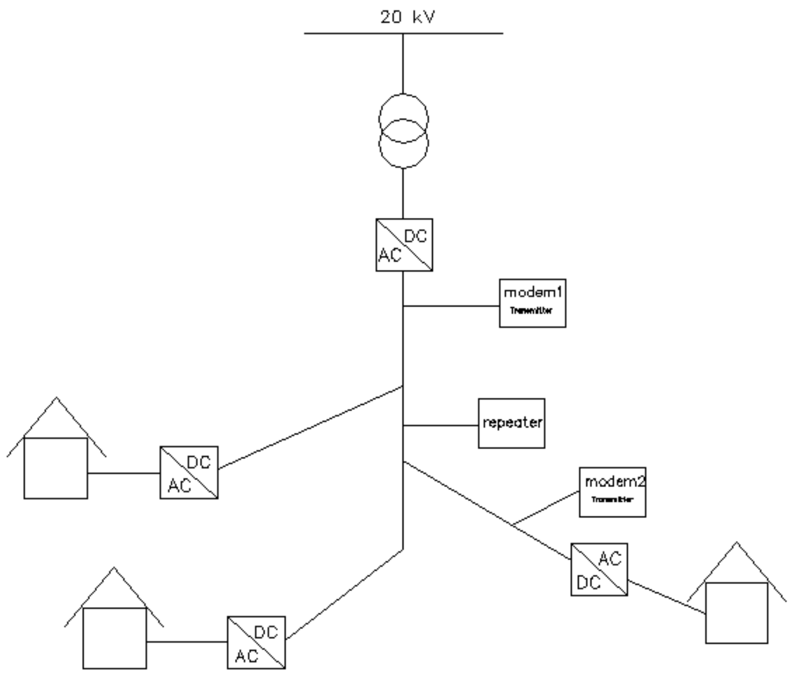


Fig.2.12. PLC system concept

The Figure 2.12 shows the main components of PLC system, which include:

- modems: transmitter and receiver
- repeater of signal (every 500 m)
- coupling devices

3 Power Line Communication in Low Voltage Networks

The LVDC network can be used as infrastructure for power line communication. However, the application of PLC sets special requirements for cables, used in the network. This chapter describes PLC history, the Homeplug 1.0 technology, the cable characteristics, and the possible optimizations in cable structure.

3.1 Background

The technology of PLC has been developing since 1838 (Brown, 1999). Nowadays, it can find a variety of applications: communication in industry (automatic meter reading, control), Internet, the possibility of telephony, different signal transfer in smart homes, and fire alarming systems. This chapter considers the development of the technology and its operating principles.

3.1.1 History of the technology

The idea of signal transmission via power lines appeared in 1838 (Brown, 1999), when Edward Davy proposed the remote supply metering. J. Routin and C.E.L. Brown patented the system, by means of which the remote measurements of the batteries voltage level in telegraph system could be carried out in the UK (Brown, 1999) in 1897. The remote reading of electricity meters using an additional wire was patented in 1905.

In 1920's the voice transmission was applied via high voltage power lines. The technology was called the carrier frequency transmission (CFS). The amplitude modulation has carrier frequency of 15 kHz – 500 kHz. If the transmission power was 10 W the distance was up to 900 km (Ahola, 2003).

For medium and low voltage distribution networks the technology of the ripple carrier signalling (RCS) was implemented. The first projects, using this technology, were the project by Siemens in Potsdam in 1930 and the project by AEG in Madgeburg and Stuttgart in 1935. The signal had low frequency (125-3000 Hz), which yields low losses. On the other hand, the required power of the signal was high: 10-110 kW. The simple modulation methods were mainly used: frequency and amplitude shift keying. The disadvantage of the method is its narrow bandwidth (Ahola, 2003).

The further development concentrated on more efficient modulation methods, decreasing of transmitting power, and the bi-directional data transfer. The first technology with reasonable price was X-10 with the carrier frequency 120 kHz and on-off keying modulation. The data rate is 100 b/s in Europe.

The development of Internet launched a new application of communication via power lines, requiring wide bandwidth. The British Norweb executed large-scale project in this area and made a conclusion of non-profitability of the project. Some projects in this field of studies were fulfilled by other European companies also, including some companies in Finland.

3.1.2 Principle of operation

For PLC over LVDC line, broadband high-frequency rang is mainly used. The physical layer (PHY) and medium access control (MAC) are covered in IEEE 1901 Draft Standard for PLC (Homeplug Power Alliance, 2010). There are two possibilities of transmission techniques: Fast Fourier Transform (FFT) – based Orthogonal Frequency Division Multiplexing (OFDM) and wavelet OFDM. The main principle of OFDM is that the spectrum is divided into several narrowband sub-carriers, each of which can have different modulation. The frequency bands for these two OFDM communication methods are: 2 – 30 MHz (optional 2-48 MHz and 2-60 MHz) for FFT OFDM and 2 – 28 MHz (optional band: 2–60 MHz) for wavelet OFDM (Galli and Logvinov, 2008).

Basically, the PLC modem (transmitter) sends signal through coupling interface to the power cable, which is used as communication medium. The other PLC modem (receiver) is also joined to the power line by coupling interface. The receiver gets the signal, which was superimposed to the power line nominal voltage, and decodes the received information. Moreover, the modem, which is used for PLC in LVDC, is a modification of standard PLC-modem.

3.1.3 Frequency bands

The European Standard EN 50065-1 defines the frequency bandwidths for Power Line Communication with and also the output transmitter voltages. The frequencies from 3 kHz to 148.5 kHz are CENELEC frequencies. The CENELEC frequencies enable only narrow band transmission. According to the standard:

- electricity suppliers should use the frequency band A: from 9 to 95 kHz.
- customers are supposed to use frequency bands B, C, and D: from 95 to 148.5 kHz.

The Figure 3.1 indicates the voltage output for signal transmission, which is defined by EN 50065-1.

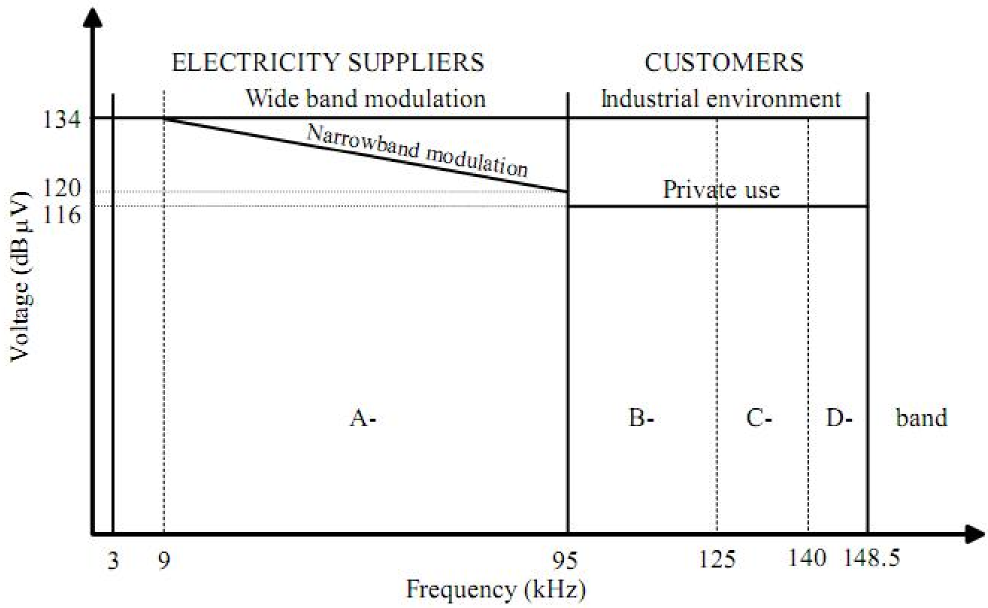


Figure 3.1. The output voltage of the transmitter according to CENELEC EN 50065-1 (EN 50065-1, 1991)

The carrier sense multiple access (CSMA) protocol is used in frequency band C. The modulation types are not specified in the standard.

As far as the level of the signal voltage is concerned, European standard EN 50160 sets limits for voltage levels of the signal transmitted over power line. The mean voltage in 3 s should be less than values in Figure 3.2 over 99% of day.

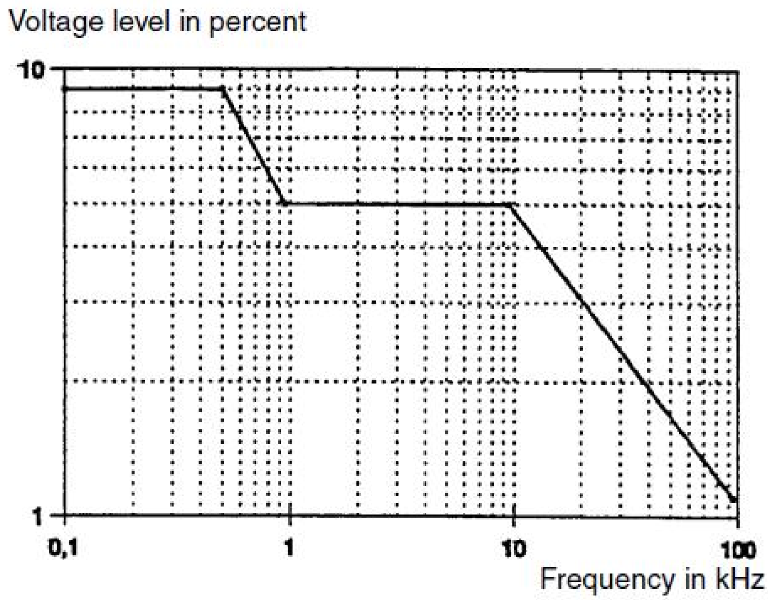


Fig.3.2. Voltage level in percent from nominal voltage for different frequencies of signal in LV distribution networks

3.2 The description of technology Homeplug 1.0 (HomePlug Power Alliance)

Normally, power lines are intended for power transmission of 50 Hz. Therefore, applying them for signal transmission emerges different issues. The parameters of power lines are not optimized for signal transmission and it causes signal attenuation. There are also different kinds of disturbances in power lines, e.g. because of the load.

The technology Homeplug 1.0 uses different methods to overcome these difficulties: special transmission technique, detection of errors, data interleaving, forward error correction (FEC means that transmitter sends information with error-correction code to the receiver), and automatic repeat request (ARQ).

Physical layer in Homeplug 1.0 uses technology Orthogonal Frequency Division Multiplexing (OFDM). The main principle is that the spectrum is divided into several narrowband sub-carriers, each of which can have different modulation. The transfer function of channel is constant, so the channel is divided into flat sub-channels and the need for complicated equalizers is eliminated.

The OFDM for Homeplug uses the frequency range from 4.5 MHz to 21 MHz and 84 equally spaced subcarriers (HomePlug Power Alliance). Cyclic prefix and differential phase-shift keying (in DPSK demodulator uses the phase change in relieved signal) –binary (DBPSK) and quadrature (DQPSK) – are used. Data interleaving and forward error correction (FEC) are employed to eliminate the data corruption by impulsive noise.

Homeplug technology employs adaptive approach, which includes choosing special modulation type, FEC, and Tone Allocation (HomePlug Power Alliance). Tone Allocation helps to struggle with heavily impaired carriers. The frame formats for Medium Access Control (MAC) are defined under the standard IEEE 802.3. Finally, Homeplug is compatible with other power line communication technologies which work on the same frequency.

3.3 Characteristics of cabling for high frequency signal transmission

The power cable parameters are frequency dependent and the dependences should be taken into account in line modelling. The calculations of the parameters can be performed with the same computation methods, as are used for radio-frequency cables.

3.3.1 Transmission line modelling

The studied line is two-wire line, because the PLC signal is coupled between two phase conductors. The other couple of conductors is not considered in the analysis. However, according to previous research (Ahola, 2003), the approximation gives results, which are suitable for channel modeling and investigation of the system. The other assumption is that the power cable acts like radio-frequency cable, hence, the same analytical equations can be used for analysis.

During signal transmission in a cable, quasi-transverse electromagnetic (TEM) wave propagates in the line. Transverse electromagnetic wave means that electromagnetic field is in the plane, which is perpendicular to the propagation direction and there are no components of electromagnetic field in the propagation direction. In practice, the cable has losses, and, consequently, it has electric field component in wave propagation direction, too.

From communication point of view cable is characterised by set of parameters. The first set of parameters is distributed resistance R, inductance L, capacitance C, and conductivity G. The other group of the parameters is propagation constant γ, characteristic impedance Z_c, and propagation speed v. They can be expressed through the first set of line parameters, as it is shown by the Equations (3.1)-(3.3).

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{3.1}$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta \tag{3.2}$$

$$v = \sqrt{\frac{1}{LC}} \tag{3.3}$$

Propagation constant consists of real and imaginary parts, which are attenuation coefficient α and propagation coefficient β. The first characterises decrease in electromagnetic field and the second – change of current and voltage phase.

The telegraph Equations (3.4) and (3.5), taking into account losses, are applicable for the system.

$$\frac{d}{dx}U(x,t) = -L\cdot\left(\frac{d}{dx}I(x,t)\right) - RI(x,t) \tag{3.4}$$

$$\frac{d}{dx}I(x,t) = -C\cdot\left(\frac{d}{dt}U(x,t)\right) - GU(x,t) \tag{3.5}$$

where *I(x,t)* – the value of current in certain point in certain time moment, *U(x,t)* - value of voltage in certain point in certain time moment.

The Equations (3.4) and (3.5) are solved for sinusoidal voltage and current, giving as a result the Equation (3.6) for voltage U_x and the Equation (3.7) for current I_x in each point of the transmission line.

$$U_x = U_o ch\, \gamma\, x - I_o Z_o sh\, \gamma\, x \tag{3.6}$$

$$I_x = I_o ch\, \gamma\, x - (U_o/Z_o) sh\, \gamma\, x, \tag{3.7}$$

where U_o is the voltage in the beginning of the line, I_o is current in the beginning of the line, x is distance from the beginning of the line.

3.3.2 Loss mechanisms

If some signal is transmitted via cable with perfect impedance matching, the losses can be classified into two groups:

- losses in conductors
- losses in dielectric material

Losses in the conductor are Joule losses; the energy is dissipated in the form of heat. The losses increase with frequency, because the higher the frequency, the more are skin and proximity effects. Actually, the rise in power losses is caused by eddy currents. In calculations it is represented by the increase of resistance. The electromagnetic field of cable induces eddy currents in the metallic parts which are situated near the cable. The energy of electromagnetic field is dissipated there, so it means additional losses. For instance, if the cable has shield of concentric conductor the losses in the shield should also be taken into account.

The other phenomena, causing energy losses, are the dielectric losses in insulation, caused by polarization. The losses can be calculated by the Equation (3.8).

$$P_\mathrm{d} = U^2 2\pi f \cdot C \cdot \tan\delta, \qquad (3.8)$$

where f is signal frequency, $tan\ \delta$ is tangent delta or dissipation factor, C is capacity. The dielectric losses begin to contribute considerably in attenuation in MHz range (Belorussov and Grodnev, 1959). But at low frequencies losses (from 0 to kHz-range) in conductor metal are the main reason of attenuation.

As far as polarization phenomenon is concerned, dielectrics have different types of polarization. The losses are caused by relaxation types of polarization, which are also called slow type of polarization. It means that the polarization state establishing requires time, which is comparable with half-period of voltage. One type of this polarization is dipole polarization. The simplest explanation of the phenomena is that molecules or their parts have not only chaotic thermal rotation, but also rotation caused by electric field. As far as power cable for LVDC is considered, the materials which are used in power cables are XLPE and PVC. XLPE is non-polar dielectric and PVC is strongly polar dielectric. Consequently, permittivity of non-polar dielectric does not depend on frequency in wide range, for polar dielectric vice versa permittivity is significantly dependent on frequency. In communication cables PVC is not implemented for insulation because of its high dielectric losses. In addition, the frequency dependences of PVC parameters on frequency result in changes in characteristic impedance of the cable, which causes reflections. Consequently, attenuation increases considerably.

The losses in insulation are proportional to dissipation factor (DF), or *tan* δ, and on relative permittivity. Polyethylene has dissipation factor less than 0.0002, while PVC dissipation factor is about 0.01 at 60 Hz. The permittivity of PVC at 60Hz is higher than the permittivity of polyethylene. So the dielectric losses in PVC exceed the losses in polyethylene (Belorussov and Grodnev, 1959).

3.3.3 Characteristic impedance

Characteristic impedance Z_c can be determined as impedance, which is faced by electromagnetic wave propagating in cable without reflection. Characteristic impedance has specific value for each cable type and depends only on *R*, *L*, *C*, and *G* of cable and current frequency. The basic definition of characteristic impedance in each point of the cable is set by the Equation (3.9).

$$Z_c = U/I\,, \tag{3.9}$$

where *U* is the voltage between terminals in the specific point, *I* is current in the circuit.

In addition, the characteristic impedance of cable can be calculated, using its parameters *R, L, C*, and *G,* according to the Equation (3.10).

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}}, \tag{3.10}$$

where *R* is cable resistance, *L* is inductance, *C* is capacitance, *G* is conductance, $\omega=2\pi f$. In case of DC *Zc* is real value, in case of AC *Zc* is complex value and consists of real and imaginary parts. It is worth mentioning that characteristic impedance can be calculated according to the Equation (3.10) in the whole range of frequencies. For high frequencies, characteristic impedance is almost constant and the Equation (3.11) can be employed.

$$Z_c = \sqrt{\frac{L}{C}} \tag{3.11}$$

In addition, characteristic impedance can also be determined using the Equation (3.12).

$$Z_c = \sqrt{Z_{oc} \cdot Z_{sc}}, \tag{3.12}$$

where Z_{oc} is impedance with opened end, Z_{sc} is impedance of cable with short-circuited end. The values of Z_{oc} and Z_{sc} are defined experimentally.

The methods of calculation cable parameters for low frequencies, in frequency band from 0 to 5 000 Hz, are described in chapter 4. For high frequencies, there are some specific features of calculation. For instance, inductance is changing because of the high frequencies. The inductance of the cable is composed of the internal and external inductance. On high frequencies, skin-effect is the reason for current to flow mainly on the surface of the conductor. Consequently, the internal inductance of the cable is negligibly small and only external inductance can be considered (Belorussov and Grodnev, 1959). The Equation (3.13) shows the dependence of external inductance L_{ex}, H/m, of two conductors in symmetrical radio-frequency cables on geometrical dimensions (Belorussov and Grodnev, 1959), if the medium between the conductors has magnetic permeability of vacuum.

$$L_{ex} = 4\ln[\frac{(2s_{diag} - d)}{d}]\cdot 10^{-7}, \tag{3.13}$$

where s_{diag} is the distance between the centers of diagonal conductors.

The capacity of the cable between diagonal conductors is calculated using the Equation (3.14).

$$C_{\mathrm{diag}} = \frac{\pi \varepsilon \varepsilon_0}{\ln(\frac{2 s_{\mathrm{diag}}}{d})} \tag{3.14}$$

where ε is permittivity of insulation material, s_{diag} is distance between centers of diagonal conductors, d is diameter or equivalent diameter of conductors, ε_0 is defined by the Equation (3.15).

$$\varepsilon_0 = \frac{10^{-9}}{36\pi} \frac{F}{m} \tag{3.15}$$

The value of permittivity for XLPE on high frequencies is 2.3. However, on high frequencies permittivity almost does not depend on frequency (Mugala et al., 2006) in the frequency range 1 - 30 MHz. When calculating the capacitance for diagonal conductors, the air between the 2 conductors is neglected.

The values, obtained from the above calculations are represented in the Table 3.1 and compared with the inductance and capacitance values obtained from calculations, which use the measured values of short-circuit and open-circuit impedances. The values are almost equal, so the Equations for capacitance and inductance are applicable for power cable.

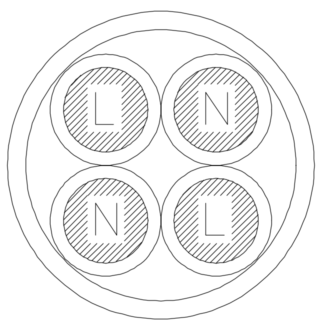


Fig.3.3. The cross-section structure of AXMK 4x16

As an example, characteristic impedance of AXMK 4x16 was calculated, using the Equation (3.11), where the inductance and capacitance were calculated according to the Equations (3.13) and (3.14). The AXMK 4x16 cross-section structure is represented in the Figure 3.3. In addition, the measurements of cable impedance with short-circuited Z_{cs} and open end Z_{os} were performed at LUT laboratory by Antti Pinomaa. The cable under investigation was AXMK 4x16 with the length 200 m. For the measurements, the impedance analyzer HP 4194A and impedance probe HP 41941A. The measurements were performed for N and N wires and for N and - 750 VDC (L) wires. For the characteristic impedance calculation, the Equation (3.12) was used. The characteristic impedance Z_{cavg} was calculated by Antti Pinomaa as an average of absolute value for all the measurements in the range from 100 kHz to 30 MHz. The inductance L and capacitance C of the cable were estimated, using the Equations (3.16) and (3.17), respectively.

$$L = \frac{Z_{\text{cavg}}\beta}{2\pi f} \tag{3.16}$$

$$C = \frac{\beta}{Z_{\text{cavg}} 2\pi f} \tag{3.17}$$

where propagation coefficient β is calculated according to the Equation (3.18), using the Equation (3.19) for computation of propagation parameter κ.

$$\beta = \frac{\text{Im}(\kappa)}{l} \tag{3.18}$$

$$\kappa = \tanh^{-1}\sqrt{\frac{Z_s}{Z_o}} \tag{3.19}$$

The results of analytical calculations and calculations, based on measurements results, are represented in Table 3.1 and in Table 3.2.

Table 3.1. The values of inductance and capacitance obtained

Analytical results		Results, obtained from experimental impedance measurements	
Inductance, [H/m]	Capacitance, [F/m]	Inductance, [H/m]	Capacitance, [F/m]
3.98×10^{-7}	4.88×10^{-11}	3.94×10^{-7}	4.28×10^{-11}

Table 3.2. The results of calculation and measurements of AXMK characteristic impedance values.

Calculated characteristic impedance between N and N conductors, [Ohm]	Measured characteristic impedance between N and N conductors, [Ohm]	Measured characteristic impedance between N and L conductors, [Ohm]
90.3	95.9	77.0

The analytical calculation of inductance has 1% difference with the value, obtained from experimental results. The result for characteristic impedance also shows good agreement on both cases. However, the capacitance analytical calculation has 14% difference with the value, calculated from experimental data. The difference between calculated analytically values and calculated from measured results values occurs because of the assumptions and simplifications, which were applied in analytical calculations. The other reason is inaccuracy of geometrical dimensions in the power cable. The inaccuracy in calculation of capacitance can affect the results in further calculations and give incorrect results, if it is used for attenuation computation. As a conclusion, the characteristic impedance and capacitance should be determined by measurements of short-circuit and open end impedances for each type of cable.

During the production of power cables no high accuracy in geometrical dimensions is applied. Consequently, the capacitance of cable and its inductance varies on the length of cable, causing the variation in values of cable characteristic impedance on its length. Therefore, signal reflections are observed, which distort the signal.

3.3.4 Signal coupling

The coupling interface is employed to separate the circuit of the cable and the circuit of PLC signal. There are two possibilities of coupling:

- inductive
- capacitive

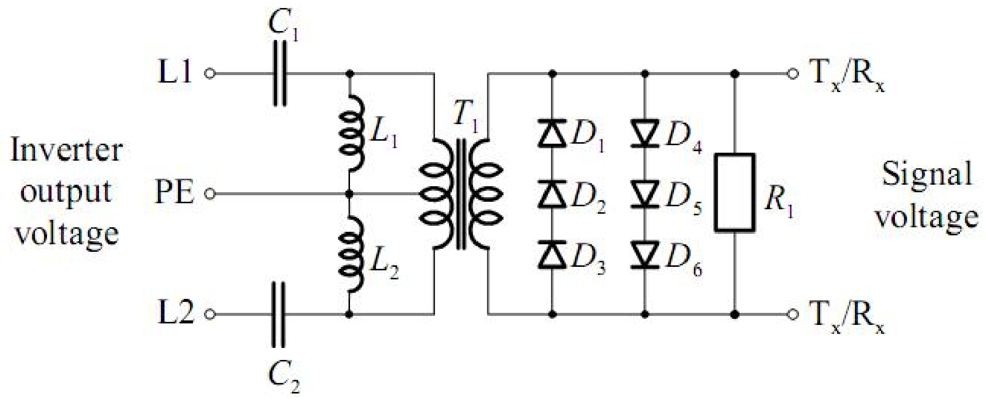


Fig.3.4. The scheme of capacitive coupling for PLC in motor cable (Kosonen, 2008).

The Figure 3.4 shows the scheme of capacitive coupling interface for PLC in motor cable (Kosonen, 2008). In case of capacitive coupling, the modem is in parallel with the main line. In contrast, if the coupling is inductive then the signal circuit is in series with the power line. The conventional capacitive and inductive coupling is applied in the frequencies below 100 MHz.

3.4 Optimization of cable structure for PLC

The LVDC cable should meet specific requirements set by PLC applications. By choosing the appropriate structure of the cable high-frequency losses can be reduced.

3.4.1 Characteristic impedance

Characteristic impedance of the cable depends on

- the per-unit parameters of the cable: resistance, inductance, capacitance, and conductance
- the frequency of signal.

The parameters of the cable are not equal along the length of the cable. Consequently, the characteristic impedance of the cable varies on its length, which causes signal reflections. As a solution, precise geometric dimensions can provide constant characteristic impedance on the whole length of the cable. However, this increases the price of cable considerably, and there is no need for precise geometry in power cables, so there is no such precision in AC power cables dimensions. Although, the research of PLC in motor cables (Konaté et al., 2010) have shown that the motor cable, which parameters are not optimized for signal transmission, is suitable for PLC for transmission lengths approximately 100 m with the allowed signal power. In this case noise is higher than in LVDC application.

Mainly, the coupling interface should have impedance matched with the characteristic impedance of the cable, so reliable signal transmission is obtained. While the characteristic impedance is calculated by the method, described in chapter 3.3.3 or computed from the measurements of short-circuit and open-circuit impedance.

3.4.2 Reduction of high-frequency losses

The losses cause attenuation of transmitted signal, so measures should be taken to reduce them. The high frequency losses are caused by losses in dielectric and in metal conductors. The reason of dielectric losses is polarization and the reason of losses in metal is Joule heat. So the minimization of losses can be done mainly by the right choice of the materials:

- non-polar insulation, for example, XLPE;
- preferably copper conductors, but aluminium is also possible.

Consequently, by choosing the power cable with XLPE insulation the high frequency losses are considerably reduced compared with PVC insulated cable.

4 LVDC power distribution

The operating conditions in LVDC system are different from the conditions in traditional AC distribution system. The differences are defined by structure, rated parameters, and other specific features of LVDC. This chapter describes cable standardisation, the possible challenges for cable in LVDC, cable modelling for LVDC, and considers the operation of existing low voltage cables in the new LVDC system.

4.1 Overview of cable standardisation

Different aspects of cable structure, operation, and testing are regulated by standards, both international and national. All the national Finnish standards requirements agree with international standards, such as IEC, CENELEC, and ISO.

One of the international standards for cables is IEC 60502-1, which defines dimensions, construction, and test methods for cables with rated voltage of 1 kV and 3 kV.

The other international standard, which is applicable for LV power cables, is IEC 60664-1. According to the standard, the solid insulation should withstand the following voltage levels:

- short-term temporary overvoltages of U_0+1200 V with durations up to 5 s
- long-term temporary overvoltages of U_0+250 V with durations longer than 5 s

where U_0 – the line-to-neutral voltage; the line-to-line voltage in neutral insulated systems.

In addition, according to IEC 60664 cable should withstand at least 12 kV with 50/1, 2µs pulse.

Consequently, in case of bipolar ungrounded IT ±750 V DC system, U_0 is 1500 VDC, and hence cable should withstand 2700 V within 5 s. The long-term temporary overvoltage with duration longer than 5 s is 1750 V.

Finnish standards SFS 4879, 5546, 4880, 2200, and 2091 specify materials, structure, test methods, and other requirements for low voltage cables with rated voltage of 0.6/1 kV. As far as DC application is concerned, these standards state that the maximum voltage against earth should not exceed 1.8 kV. The DC system, in which the cable is used, should have rated voltage between conductors not higher than 1.5 kV.

4.2 Possible challenges

The rated current is one of the main parameters in choosing the cross-section of cable. The rated current of the system is estimated according to the power demand and should match power cable rated current. However, the economical selection and other parameters, like voltage drop, lead usually to choice of cable cross-sections, rated current of which is high enough for normal operation.

The possible over-voltages and short-circuit currents should be also taken into consideration in cable choice.

4.2.1 Voltage stress

One of the most important operating parameters for cable is rated voltage. Cable should work without insulation faults under the rated voltage. The rated voltage for the cable in bipolar system is ±750 V DC. The connection of the cable for this system is represented in Figure 4.1 and *U* is the rated voltage.

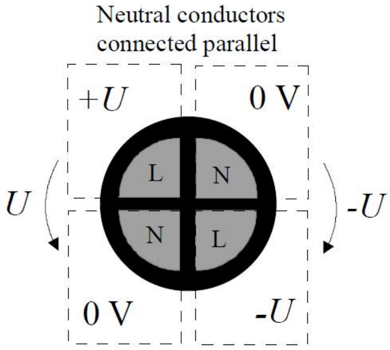


Fig.4.1. The connection of AXMK 4-wire cable for LVDC bipolar transmission line (Salonen et al. 2008).

Standards for AC cables with rated voltage of 0.6/1 kV enable the implementation of the cables if rated voltage between conductors is not higher than 1.5 kV, and the voltage between conductors and earth does not exceed 0.9 kV for grounded system. Consequently, the existing AC cables can be used in LVDC system. Furthermore, the overvoltage withstand capacity should be at least on the level, set by IEC 60664-1, which means that cables should withstand switching overvoltages of the system.

Fault in the system can cause over-voltages. The earth fault of the LVDC network changes the distribution of voltage between the conductors. As a result, the voltage exceeds the rated voltage, but the voltage stress is not higher than 1.5 kV and it is cleared by insulation monitoring device. The clearance time is small enough and the over-voltage does not cause any damage to the cable.

The other threat is lightning over-voltages that occur in medium voltage 20 kV overhead lines, affecting low voltage distribution network as well. However, the most sensible components to this kind of over-voltages are converters and feeding transformer. As a result, the protection equipment should be chosen in such way that it protects the converters effectively. For cable protection, T. Suntila proposed in his Maser's thesis use of metal oxide protectors with drop out voltage of 3 kV (Suntila, 2009). However, cables are less sensible to the lightning disturbances, caused by lightning, so if the converters are protected from these disturbances, then it automatically guarantees reliable protection for cables. For this reason, the lightning over-voltages should not be taken into account in cable selection.

4.2.2 Maximum current

The stability of LVDC system was studied at Lappeenranta University of Technology. Figure 4.2 depicts the results of the investigation. If the economical range of LVDC applicability is considered and system is dimensioned on economical basis, then the conclusion is that system always operates within its stability limits.

Concerning cable, its reactance is small compared with that of other components of the system, consequently, changing cable parameters does not influence on the system stability. For instance, the minimum capacitor for a single converter (with load of 10 kW, 750 V) LVDC pole is 1563 μF (Korshun, 2009), while the computed capacitance of 200 m of AXMK cable is 9.8 nF.

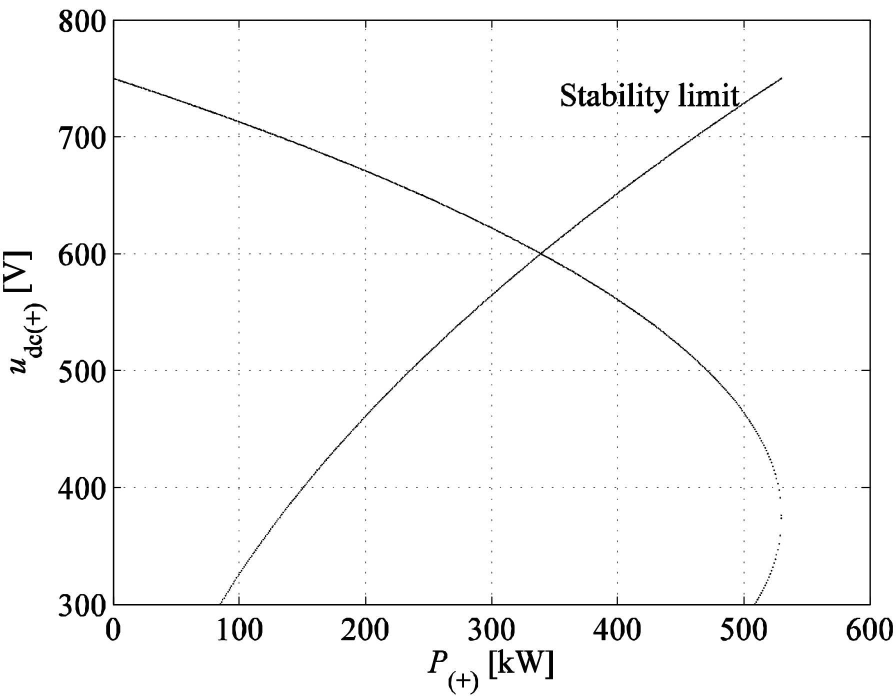


Fig.4.2. The LVDC system stability (Partanen et al., 2010)

Some fault situations can occur in LVDC system, during which the network can be short-circuited. The short-circuit current exceeds rating current several times, causing excessive heating of the cable. While cable materials, namely, metal and polymer, can stand temperature within certain limits. If the temperature is high, it causes polymer degradation and even melting. In addition, extremely high temperatures can cause metal melting. So each cable can withstand certain maximum current some period of time. These currents are calculated for each type of cable and given in standards and by producers in datasheets.

In SFS 4879, the short-circuit currents for 1 s were calculated with the following assumptions (SFS 4879):

- start temperature for XLPE insulated cable is 90 ^{0}C
- final temperature for XLPE insulated cable is 250 ^{0}C
- the value of short circuit current for time t=0.2-5 s can be calculated by dividing the current value for 1 s by $\sqrt{t}$

The Table 4.1 gives the values of short circuit current for 1 s and 5 s for XLPE-insulated cable with aluminium conductors.

Table 4.1. Permissible short-circuit currents and power capacity for XLPE cable with aluminium conductors for 0.6/1kV (e.g. AXMK)

Cross-section, mm^2	Short-circuit current for 1 s (SFS 4879), kA	Short-circuit current for 5 s, kA	Power capacity at 750 V DC, kW
16	1.5	0.67	58.5
25	2.4	1.07	75.00
35	3.4	1.52	93.75
50	4.8	2.15	112.5
70	6.7	3.00	138.7

From the other side, these values should be compared with the values of short-circuit current calculated for the system, and the time, during which the protection clears the excessive current. So the permissible short-circuit current for the cable should be less than maximum short-circuit current in the system or equal to it.

In LVDC system, the maximum current will occur in case of short circuit between positive and negative pole. Earth fault current will be small, because the system under consideration is IT-ungrounded system. For the short-circuit current computation, the following assumptions are made: firstly, the voltage at the fault point before the fault is equal to nominal voltage, the secondly, the normal load currents are not considered, because they are negligibly small compared with short-circuit currents (Lakervi and Holmes, 1998). The equivalent scheme for short-circuit between two poles of bipolar system is represented in the Figure 4.3, where Z_1 represents the primary transformer winding in equivalent circuit and Z_2 represents the secondary winding. the impedance of short-circuit is neglected and the rectifier impedance is also not considered, because it has small value compared with the impedance of the transformer (Salonen et al., 2008b).

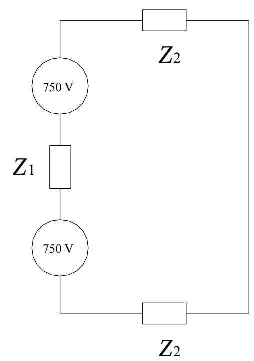


Fig.4.3. The equivalent circuit for short-circuit situation between the two poles of bipolar system

The impedance Z_1 is calculated by multiplying the magnitude of primary transformer impedance, calculated to the low voltage side of the transfomer, by ratio 1.35, which represents how the Z_1 is seen from DC side. The impedance Z_2 is calculated, using the same method.

In accordance with Thevenin's theorem, the computation of short-circuit current I_s is fulfilled using the Equation (4.1), where all values are phasors.

$$I_{sc} = \frac{U}{Z_f + Z_i}, \tag{4.1}$$

where U – the voltage at fault place before the fault, Z_f is impedance of short circuit, Z_i is impedance of the network seen from the fault place. Typically, the feeding 20 kV grid can be considered rigid, and, hence, the transformer impedance becomes defining.

The Table 4.2 shows the total transformer impedance for the short-circuit between the two poles and the results of short-circuit current estimation with the assumptions, indicated above.

Table 4.2. The dependence of short-circuit current on transformer rated power

Rated power of transformer S_n, [kVA]	The transformer impedance seen from DC-side Z_i, [Ohm]	Short-circuit current I_{sc}, [A]
30	0,763	1966
50	0,458	3275
100	0,223	6727
200	0,117	12779
315	0,074	20158
500	0,054	27838
800	0,035	43339
1000	0,029	51100

The Figure 4.4 depicts the dependence of short-circuit current on transformer power. However, it should be considered that this plot represents estimation of short-circuit current values, and more precise calculations are recommended.

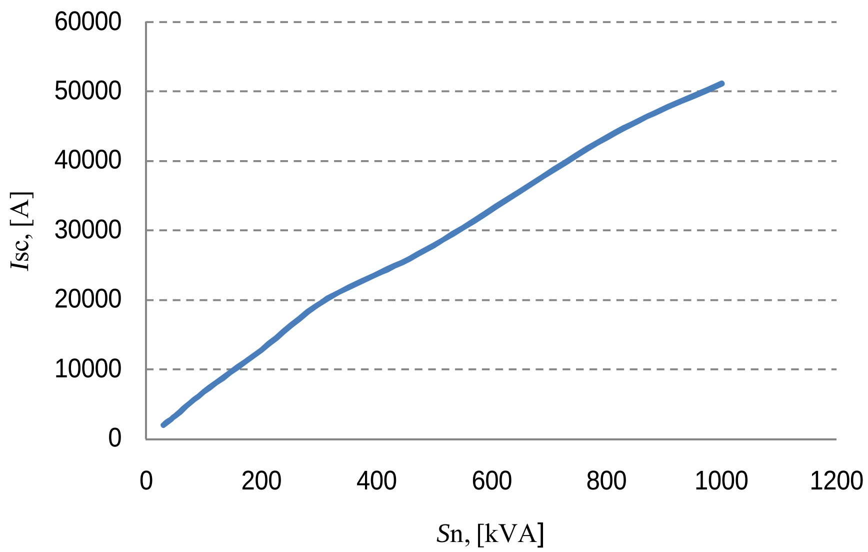


Fig.4.4. The dependence of short-circuit current on transformer power

Using the obtained results, the short-circuit currents of the system are compared with the currents, which cable can withstand, then the appropriate cross-section of the cable is chosen. For example, if the 30 kVA transformer is used, then cable with 50 mm^2 cross-section can be applied after rectifier, because 5 s maximum current of 50 mm^2 exceeds the maximum short-circuit with 30 kVA transformer. However, short-circuit current will reduce along the cable length after junction points as the total impedance will increase. This fact leads to a possibility of using smaller cross-sections further from rectifier. Short-circuit currents should be always considered when dimensioning the network.

4.2.3 Electromagnetic Interference

The current in LVDC contains not only the direct current components, but also high-frequency components, superimposed on the DC current. The tests on prototype of LVDC were performed at LUT, and the values of voltage and current were measured. The prototype includes transformer, two 6-pulse rectifiers, inverters, and cable AXMK 4x16, which length is 200 m. The Figure 4.5 depicts frequency spectrum of current in prototype loaded with 5 kW. These high-frequency components can affect normal operation of the cable, accelerating ageing processes in cable insulation. On the other hand, they should comply with the existing EMI standards.

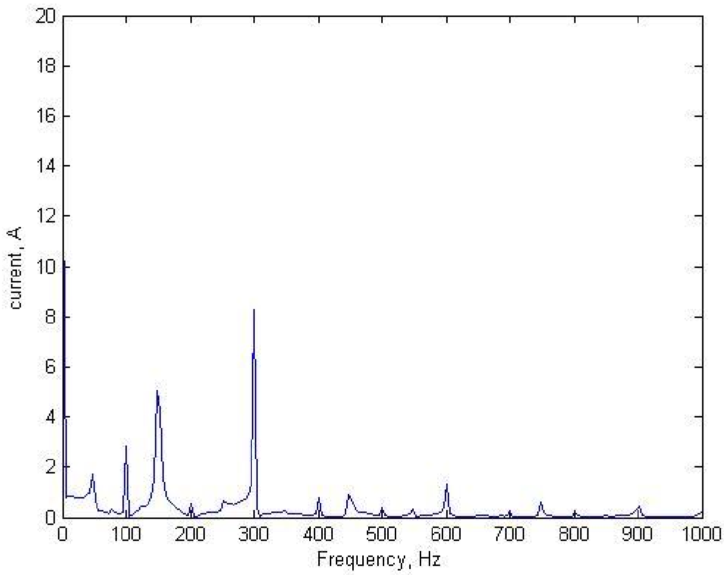


Figure 4.5 Frequency spectrum of current in LVDC prototype with the load of 5 kW

Previously, the influence of the high frequency components on the cable insulation was studied in Japan. The case of PWM modulation for AC-cable with XLPE insulation was investigated. As a result, the conclusion was that high-frequency components in this case do not contribute into the degradation of insulation, because of low magnitude of the high-frequency components. As a result, they should not be taken into account in the calculation of insulation thickness (Seki et al., 1994). The same can be concluded for the case of LVDC cable: the high-frequency components of the DC do not accelerate the degradation process of the insulation.

Similarly, the influence of the electro-magnetic field of the cable on the environment is not considerable. The cable in the LVDC system is underground cable, so the electromagnetic fields, caused by the currents in cable, attenuate, when the distance from the cable grows. In addition, the cable contains two lines with opposite polarity and the fields from these lines partly compensate each other when the line is symmetrically loaded. If the concentric conductor is used in the cable, then it acts like shield and also reduces the electromagnetic emissions.

4.2.4 Installation techniques

The cable for LVDC will be used in underground constructions. So it should be suitable for outdoor installations with ambient temperature range from -40 to +60 ^{o}C. In addition, when cable line is constructed, the recommendation of minimum temperature for cable installation should be considered. In case the temperature of cable is lower than recommended, the cable should be preheated (SFS 4879).

The other important environmental condition is soil thermal resistance, which affects considerably on rating current of the cable. Rating currents for cables are calculated for specific soil thermal resistance and indicated in standards. For instance, for cable AXCMK the soil resistance in calculations is assumed to be 1 K*m/W (SFS 4880). Hence, the actual value of soil thermal resistance should be considered in current rating calculations by using correction factors according to standard recommendations. Therefore, the soil thermal resistance should be measured along the way, where the cable is installed.

When cable line construction is planned, the mechanical properties of the cable should be also considered. One of them is the minimum radius for cable line, the requirements for which are set by cable standards.

Mechanical stress for cable is also created, because the cable line is in many cases constructed by ploughing. As a result, cable materials should withstand the mechanical stress of ploughing. So PVC jacket can be used, but its mechanical properties are lower than that of PE jacket. PVC is moisture resistant and PE has low water permeability. However, during exploitation the content of plasticizers in PVC decreases, and it becomes less resistant to low temperatures and to moisture, than in the beginning of exploitation. PE changes its properties during exploitation less than PVC.

Standard 6000-8-814 recommends AMCMK, AXCMK, MCMK, AXMK, AXMKE and other cables with appropriate producer recommendations for installations in ground.

4.3 Cable modelling in network calculations

Cables, as part of LVDC system, should be considered in network modelling. For instance, frequency dependences of cable parameters should be estimated, as well as power losses and voltage drop. The possible influence of cable parameters on the system functioning should be also considered.

4.3.1 Frequency dependences of cable parameters

As the direct current in the LVDC contains high frequency components, the cable parameters are considered in regard to the frequency value.

The resistance of cable on alternating current is higher than the resistance on direct current because of skin-effect and proximity effect. The mechanisms of skin-effect are described below. At first, magnetic field of the conductor current causes eddy currents in the conductor. The eddy currents have the same direction as main current near the conductor surface and the opposite direction in the middle of the conductor. Hence, the uneven distribution of current density is observed in the cross-section of the conductor: higher current density is close to the conductor surface.

Another effect, causing the rise in resistance value on high frequencies, is proximity effect. Consequently, the current density is distributed unevenly in the cross-section because of the presence of the second conductor. The mechanism of the proximity effect is as follows: the electromagnetic field of the first conductor induces eddy currents in the second conductor. These eddy currents have the same direction as the main current of the second conductor on the side of the conductor, which is closer to the first conductor, and they have the opposite direction to main current on the other side. Finally, the current density (if main currents in the conductors flow in opposite directions) on the sides of conductors, which face each other is more than on the other sides.

If the current is alternating the cross-section is not used in the same way as in case of direct current, actually, it is used less effectively. Some areas of the conductor have high current densities and some have low, so in calculations it is modelled by the increase of resistance.

In power cables, when computing the increase in resistance, in most cases skin-effect and proximity effect are taken into consideration. The resistance for alternating current is given by the equation (4.2) (Anders, 2005).

$$R = R_{DC}(1 + y_s + y_p), \tag{4.2}$$

where R_{DC} is the resistance of the cable on the direct current, y_s – considers the skin-effect, y_p – considers the proximity effect.

The parameter showing the increase in resistance due to skin-effect is computed by the Equation (4.3) (Anders, 2005), in case if $x < 2.8$.

$$y_s = \frac{x_s^4}{192 + 0.8 \cdot x_s^4}, \tag{4.3}$$

where x_s^2 is determined by the Equation (4.4).

$$x_s^2 = \frac{8\pi f \cdot k_s \cdot 10^{-7}}{R_{DC}}, \tag{4.4}$$

where f is the frequency of signal, k_s is coefficient, which depends on the form of conductor. For copper conductors round or sector-shaped, aluminium round and stranded $k_s = 1$ (Anders, 2005).

For the 2-core cable the proximity effect can be calculated according to the Equation (4.5):

$$y_p = \left(\frac{d}{s}\right)^2 \cdot \frac{x_p^{\ 4}}{192 + 0.8 \cdot x_p^{\ 4}}, \tag{4.5}$$

where d is the diameter of the conductor, s is the distance between the centres of the conductors, x_p can be determined according to the Equation (4.6).

$$x_p^{\ 2} = \frac{8\pi f \cdot k_p \cdot 10^{-7}}{R_{DC}}, \tag{4.6}$$

where k_p is coefficient, which depends on the form of conductor. IEC 60287 recommends the same values of k_p for stranded conductors both copper and aluminium (Anders, 2005). For non-dried and non-impregnated copper conductors the values of k_p are as follows (Anders, 2005): round, stranded; round, compact; and sector-shaped: 1; dried and impregnated sector-shaped: 0.8.

The increase in resistance due to skin-effect and proximity effect is shown in Figure 4.6 and 4.7 for AXMK 4x35 at 20 ^{0}C in assumption that current flows only in one vertical couple of the conductors. The Equation (4.3) is applicable for cable AXMK 4x35 if the frequency is lower than 2700 Hz, because in this case $x < 2.8$.

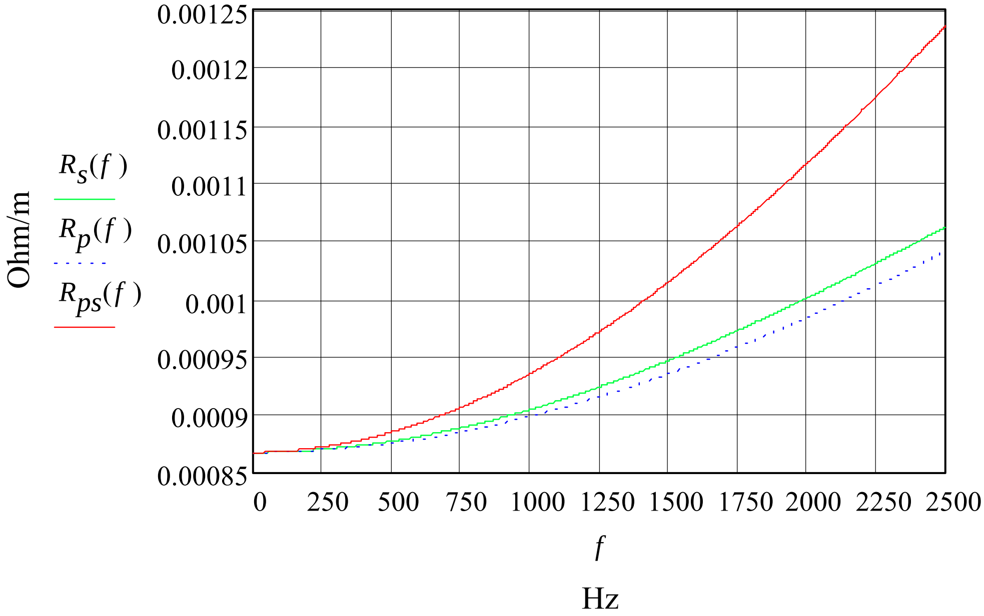


Fig.4.6. The dependence of AXMK 4x35 resistance on frequency taking into account: $R_s(f)$ – skin-effect, $R_p(f)$ – proximity effect, $R_{ps}(f)$ – both proximity and skin effects.

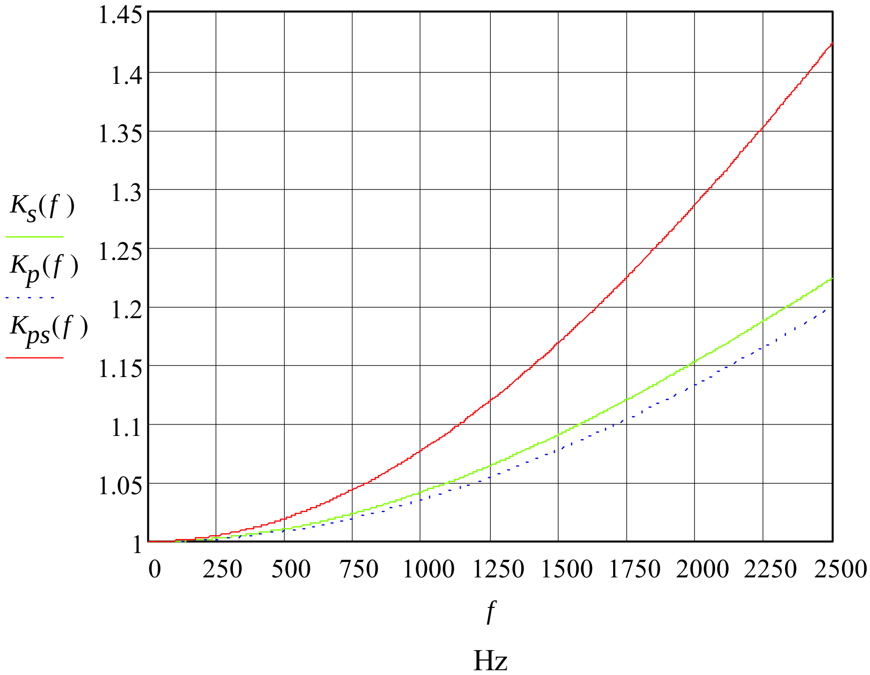


Fig.4.7. The dependence of R_{ac}/R_{dc} of AXMK 4x35 on frequency taking into account: $K_s(f)$ – skin-effect, $K_p(f)$ – proximity effect, $K_{ps}(f)$ – both proximity and skin effects.

The Figure 4.7 shows that at frequency of 1500 Hz the increase in resistance is about 17%, while for 50 Hz it is only 0.02%. The skin and proximity effects are increasing with frequency. Consequently, the losses on high frequencies rise considerably.

The resistance change with frequency, in assumption that current flows only in diagonal couple of conductors, is calculated with the same equations as for vertical couple of conductors. The skin effect in the assumption will be the same, while calculating proximity effect another value of distance between conductors is substituted. Figure 4.8 shows the raise in conductor resistance with frequency at 20 ^{0}C. Figure 4.9 depicts the dependence of R_{ac}/R_{dc} on frequency.

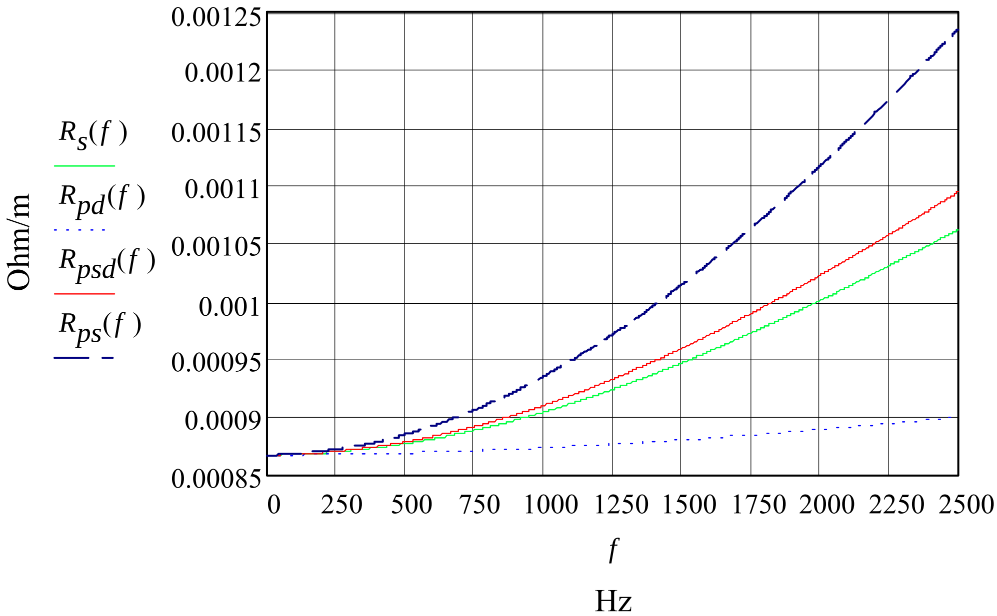


Fig.4.8. The dependence of AXMK 4x35 resistance on frequency (taking into account: $R_s(f)$ –skin-effect, $R_{pd}(f)$ – proximity effect, $R_{psd}(f)$ – both proximity and skin effects, $R_{ps}(f)$ – both proximity and skin effects (current flows in vertical couple of conductors)

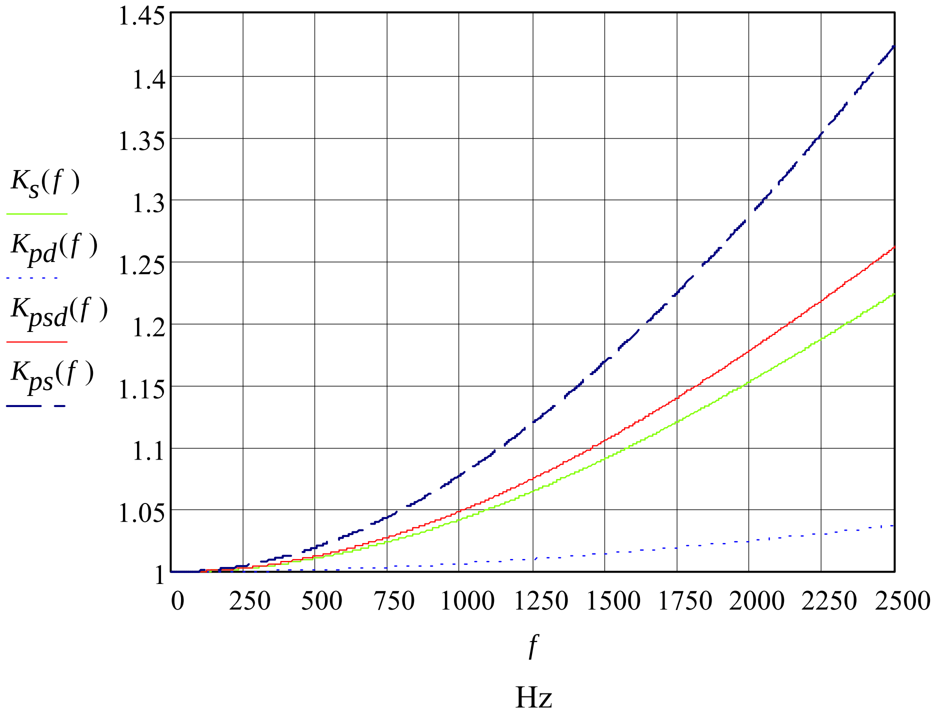


Fig.4.9. The dependence of R_{ac}/R_{dc} of AXMK 4x35on frequency current flows in diagonal couple of conductors) taking into account: $K_s(f)$ –skin-effect, $K_{pd}(f)$ – proximity effect, $K_{psd}(f)$ – both proximity and skin effects, $K_{ps}(f)$ – both proximity and skin effects (current flows in vertical couple of conductors)

In cable lines at 50 Hz, the reactance is mainly constituted by capacitance and inductance is relatively small. The capacitance of the cable in F/m can be calculated by means of the Equation (4.7) (Grigsby, 2007). Actually, the result represents the cable phase-to-ground capacitance (Anders, 2005), for example, in case of one-conductor cable with earthed shield.

$$C = \frac{2\pi\varepsilon \cdot \varepsilon_0}{\ln \frac{D}{d}}, \tag{4.7}$$

where D – diameter of insulation under insulation shield, d – diameter of the conductor, ε - relative dielectric permeability of insulation, ε_0 is dielectric constant, which value is defined by the Equation (4.8).

$$\varepsilon_0 = \frac{10^{-9}}{36\pi}\frac{F}{m} \tag{4.8}$$

In the case of the connection, shown in Figure 4.1 the calculation of capacitance between L and N can be fulfilled by modifying the equation given for overhead one-phase line with two round conductors in Grigsby's book (Grigsby, 2007). The assumption is made that two conductors are close to each other and there is now air space between them. Also, the value of equivalent radius of sector conductors is used for computation. Then the capacitance F/m can be calculated by using the Equation (4.9).

$$C = \frac{\pi \cdot \varepsilon \cdot \varepsilon_0}{\ln\left(\frac{2s}{d}\right)}, \tag{4.9}$$

where s is distance between the centers of conductors.

For AXMK 4x35 the Equation (4.9) gives the value C = 1.109x10^{-10}F/m or 0.1109 µF/km.

Another way to calculate the capacity was proposed by Martin Høgdahl Jensen and Birgitte Bak-Jensen in their paper "Shunt admittance of the four-wire distribution cable with sector-shaped conductors" .The capacity between the conductors is calculated in assumption that they act like plate capacitor (Jensen and Bak-Jensen, 2001). The method showed good agreement with experimental results, so the capacity calculation for cable can be made by the Equation (4.10).

$$C_{\text{plate}} = \varepsilon \cdot \varepsilon_0 \cdot \frac{b_{\text{h}}}{2 \cdot h_{\text{ins}}}, \tag{4.10}$$

where b_{h} is the height of sector, h_{ins} - insulation thickness.

The capacity of AXMK 4x35, obtained by employing the Equation (4.10) is $7.731x10^{-11}$F/m or 0.07731 µF/km, which has the difference with the result of the Equation (4.9) of 30%. So, it is preferable to use the Equation (4.10), because the operating capacitance given by producer (Draka NK Cables Ltd.) is 0.29 µF/km.

For diagonal conductors the Equation (4.10) cannot be used in the given form, because cable contains air in the center. However, the capacity calculation can be fulfilled by the Equation (4.11) (Jensen and Bak-Jensen, 2001), which is modification of the Equation (4.10).

$$C_{\text{diag}} = \frac{A_{\text{g}}}{2 \cdot \frac{b_{\text{h}}}{\varepsilon_0 \cdot \varepsilon} + \frac{A_{\text{g}}}{\varepsilon_0}}, \quad (4.11)$$

where A_{g} is the distance of air between the two conductors.

The capacity for diagonal conductors of AXMK 4x35 is $1.94x10^{-12}$ F/m or 1.94 nF/km.

If capacitance is known, then capacitive reactance (between vertical conductors), Ohm*m, can be calculated by the Equation (4.12).

$$X_C = \frac{1}{2 \cdot \pi \cdot f \cdot C}, \quad (4.12)$$

where f is current frequency.

The total reactance of the cable is composed of inductive and capacitive reactance. Due to small distances between the conductors in cable, the inductive part of reactance is small, but it increases with frequency. The inductance of cable per meter can be calculated using the Equation (4.13) (Grigsby, 2007) and it depends on the geometrical configuration. The Equation (4.13) considers both the internal inductance of the conductor and the external inductance.

$$L = \frac{\mu_0}{2\pi}\left(\ln\left(2\frac{s}{d}\right) + 0.25\right), \tag{4.13}$$

where s is distance between the centers of conductors, d is diameter of the conductor, μ_0 is vacuum permeability and is defined by the Equation (4.14).

$$\mu_0 = 4\pi \cdot 10^{-7} \frac{H}{m} \tag{4.14}$$

The Equation (4.13) gives the inductance of the circuit composed of two parallel conductors (Whitaker, 1999). The obtained result for AXMK 4x35 is 1.75×10^{-7} H/m or 0.175 mH/km.

For diagonal conductors inductance is calculated in accordance with the Equation (4.13), but the value of s will be different from the previous case. The inductance of AXMK 4x35 is 2.59×10^{-7} H/m, or 0.259 mH/km. The value of inductance given by producer (Draka NK Cables Ltd.) is 0.28 mH/km, which corresponds well with the results of calculations, so the Equation (4.13) can be used for inductance calculations at low frequencies, because the Equation includes both internal and external inductances for cable. Meanwhile, for the signal in MHz bandwidth, skin-effect increases considerably and current mostly flows on the surface of the conductor, resulting in decrease of internal inductance. Hence, the external inductance should be mainly taken into account.

The inductive reactance, Ohm/m, can be calculated by using the value of inductance with the Equation (4.15).

$$X_L = 2\pi f \cdot L \tag{4.15}$$

The dependences of capacitive and inductive reactance are presented in Figure 4.10. The inductive reactance for cable has much lower value than capacitive reactance, which can be explained by small distance between the conductors.

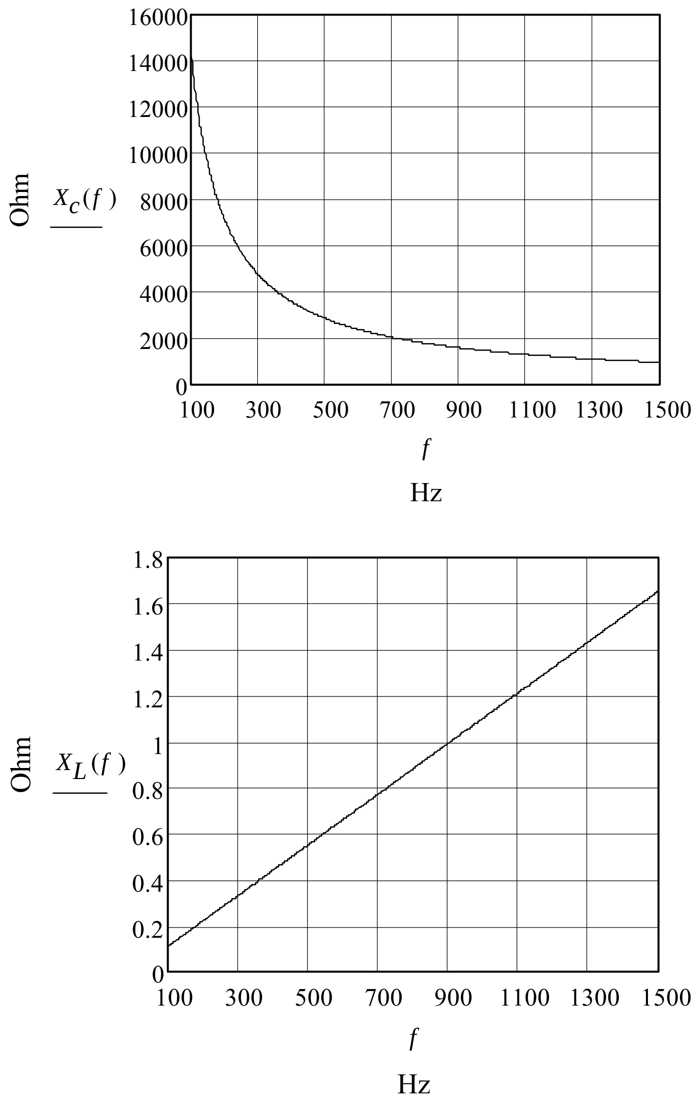


Fig. 4.10. Frequency dependence capacitive and inductive reactance of 1 km AXMK 4x35

Conductivity of insulation can be determined using the Equation (4.16).

$$G = \omega\, C \tan\delta \tag{4.16}$$

For cable AXMK 4x35 for diagonal conductors the dependence of conductivity on frequency is represented in Figure 4.11, where the dependences of *C* and *tan δ* on frequency were neglected. The insulation has high quality, so the conductivity has low value.

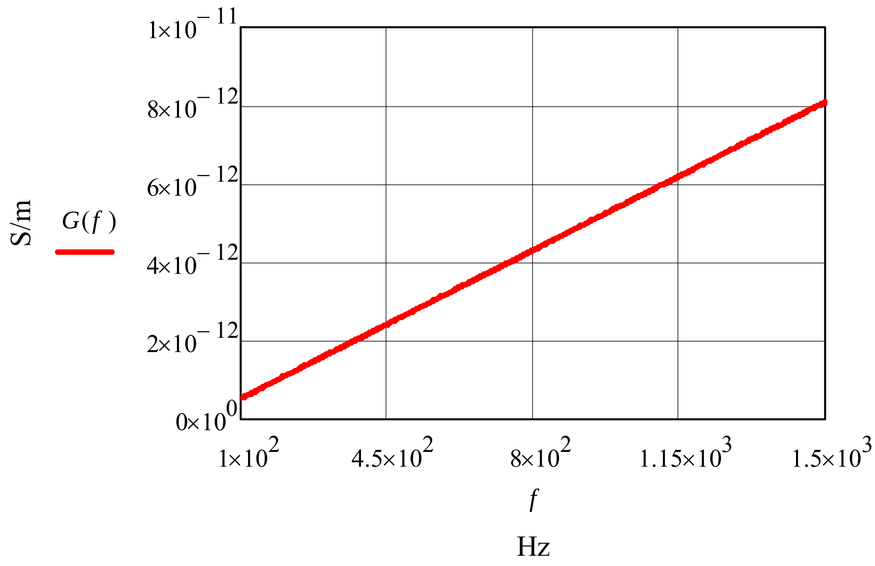
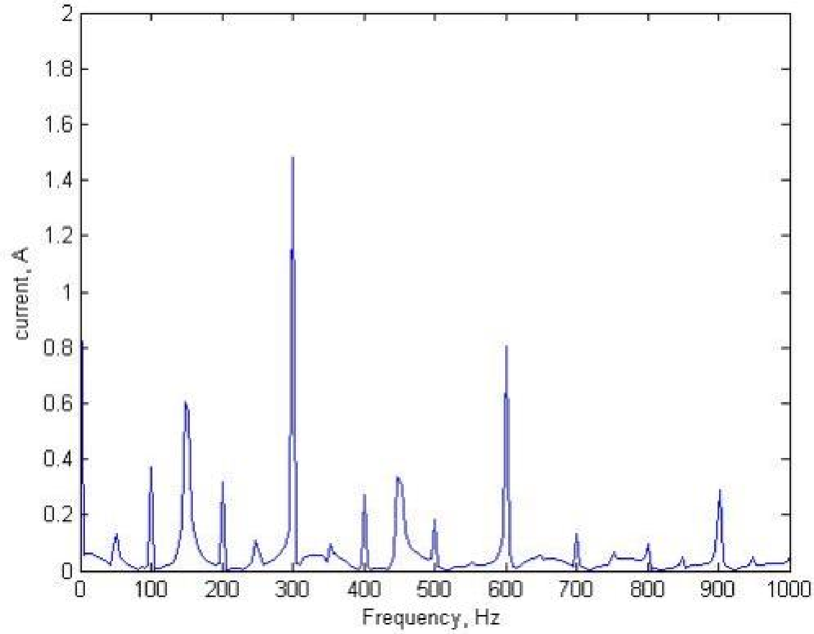


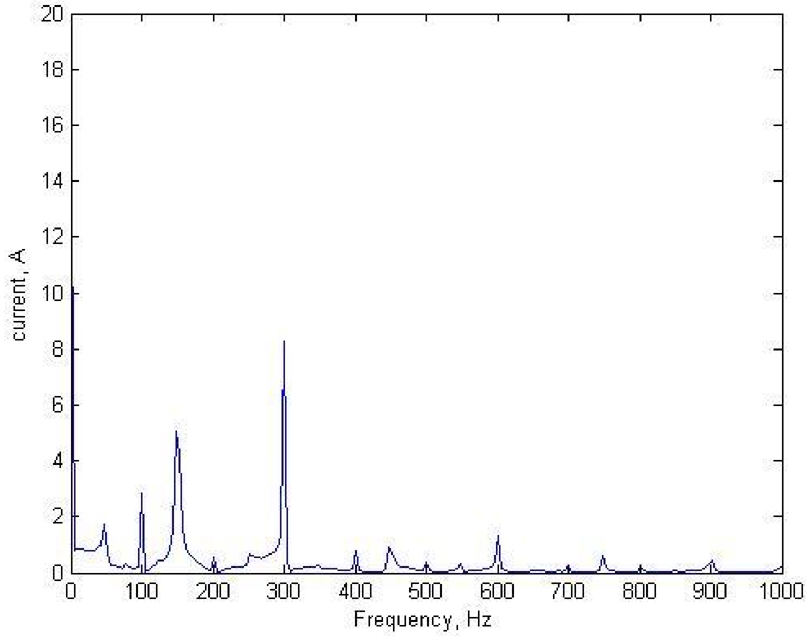
Fig. 4.11. The dependence of conductivity of AXMK 4x35 insulation on frequency

4.3.2 Impacts of cable parameter selection

The cable is important part of distribution system. It provides the transmission of energy from the rectifier to inverter. The current in the cable should be direct current, but actually it contains distortion of different frequencies. However, the cable does not influence on the form of voltage and current, because other components of the system have capacities, inductances and other parameters, which exceed cable parameters several times. In addition, for low the line current harmonic components, which are have considerable magnitude at frequencies not higher than 300 Hz, the power cable can be considered electrically short. Consequently, these components, and not cable, influence the form of electric signal in the line. For instance, the Figure 4.12 represents the changes in current spectrum from the non-loaded system to loaded system.



a)



b)

Fig.4.12 Current spectrum for LVDC prototype: a) – no load; b) – 5 kW load

If the power losses and voltage drop are considered, cable parameters should be taken into account. Mainly, cable resistance is important, so cable cross-section is chosen in consequence with required power capacity, line length, and the voltage drop limit.

In short-circuit currents and earth fault calculations, the parameters of transformer and converter give main contribution, because they exceed cable parameters considerably.

4.3.3 Power losses and voltage drop in cable

One of important characteristics for distribution line is voltage drop, which is the difference between voltage at the beginning of the line and at the end of the line. The voltage drop becomes more significant, when the line length increases. The example for dependence of voltage drop on cable length is given in Figure 4.14 for AXMK 4x35 with load of 10, 12, 14, 16, 18 kW at temperature +65 ^{0}C. Consequently, voltage drop sets limits for the choice of cross-section at certain line lengths.

The voltage drop for one pole of bipolar system with two neutral conductors connected in parallel is calculated according to the Equation (4.17).

$$U_{\mathrm{d}} = r \cdot I \cdot l, \qquad (4.17)$$

where r is the pole resistance of the cable per km, l the length of the cable in km's, and I the pole current.

The dependence of voltage drop on power demand P is obtained by substituting the current as a function of receiving end node voltage, U (750 V), and power demand (P) of a single pole. The Equation (4.18) represents the obtained dependence.

$$U_{\mathrm{d}} = r \cdot \frac{P}{U} \cdot l \qquad (4.18)$$

The calculations of resistance are given in Appendix 1. The voltage drop in per cents is defined by the Equation 4.19.

$$U_d = r \cdot \frac{P}{U \cdot U_N} \cdot l\,, \tag{4.19}$$

where U_N is rated voltage for the system.

As an example, the dependence of voltage drop in cable AXMK 4x35 on length was calculated for one pole of bipolar system for different transmission power. In, addition, the neutral conductors are parallel connected as it is shown in Figure 4.1. The obtained dependences are shown in the Figure 4.13.

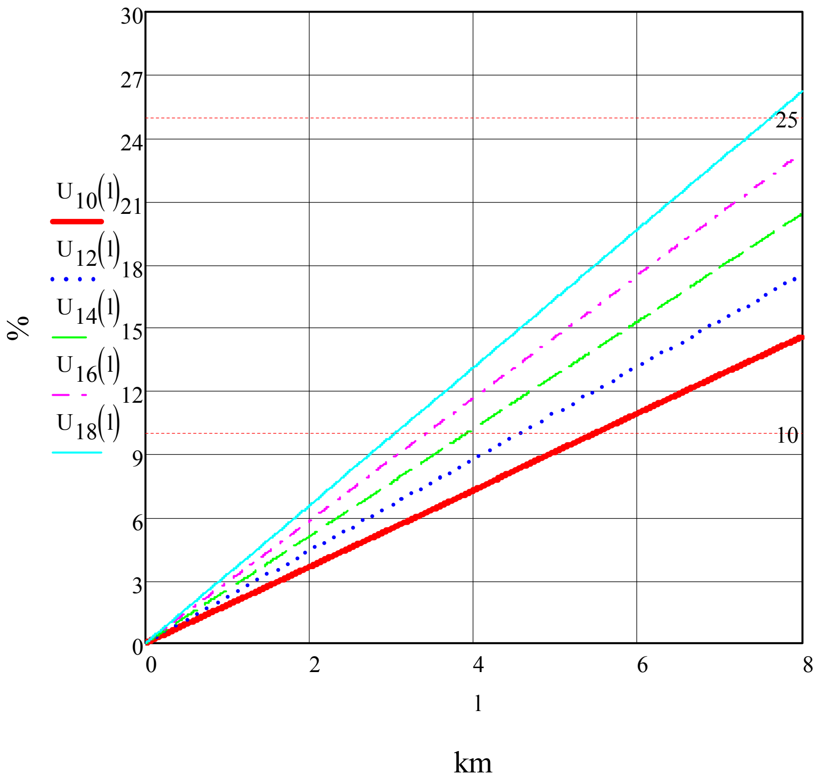


Fig.4.13. The dependence of voltage drop on cable length for AXMK 4x35 at 65 ^{0}C. The sub-indexes of voltage drop show the power of load in kW

In addition, voltage drop depends on power capacity. The Figure 4.14 depicts the dependence of voltage drop on power capacity for 1 km of cable. The maximum voltage drop is 25%, which allows the converter on customer side to produce the required voltage. The voltage drop is not exceeded even in the cable with the smallest cross-section 16 mm^2.

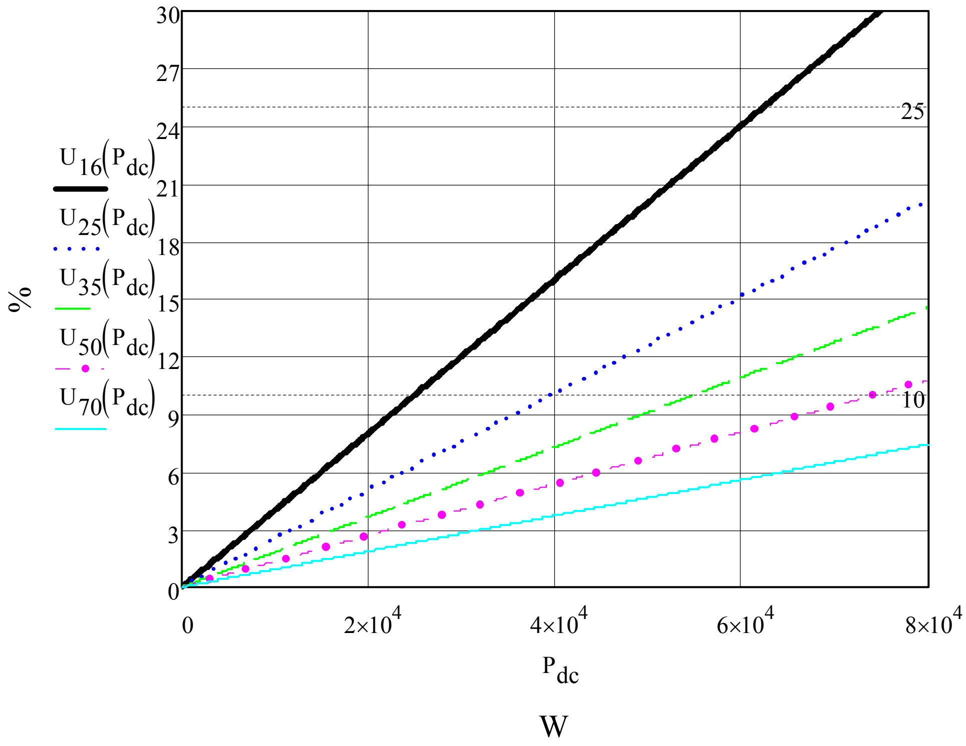


Fig.4.14. The dependence of voltage drop in Al cable conductors at 65 ^{0}C with different cross-sections in per cents on power capacity. The sub-scripts of *U* represent cross-section in mm^2

The voltage and current in the DC link have harmonic components, superimposed on the DC. These components create additional losses in cable, both losses for Joule heat and dielectric losses. The total loss can be calculated as sum of losses on all frequencies.

Power losses in cable change into heat, which increase the temperature of cable above the ambient temperature. The temperature difference between cable and environment is determined by the power capacity, the thermal properties of cable components, and the thermal properties of the environment. Another point is that, according to the Arrhenius law, the heating accelerates thermal ageing of polymers. In addition, for polymers maximum operating temperature is limited, for XLPE operating temperature is 90 ^{0}C, and for PVC is 70 ^{0}C. These are the reasons for power losses to be considered.

Tests were performed at LUT laboratory by Andrey Lana on the LVDC line prototype with one pair of AXMK 4x16 cable conductors loaded by 5 kW. Current in the line and voltage both in the beginning of the line and in the end of the line were measured. Then Discrete Fourier transform was applied to obtain current and voltage spectrum, so peak values of harmonic components were calculated. For power loss calculations, the route mean square values (RMS) are required, which are obtained by dividing both current and voltage magnitude by $\sqrt{2}$. Finally, power losses in the line for different frequencies are calculated according to the Equation (4.17).

$$P_{\text{loss}} = \Delta u \; i/2 \tag{4.17}$$

where i is the current peak value and Δu is the difference between the peak voltages in the beginning and in the end of the line.

For DC component the power loss is defined by peak values is calculated according to the Equation (4.18).

$$P_{\text{lossDC}} = \Delta U \; I \tag{4.18}$$

The power loss calculation results are depicted in the Figure 4.15.

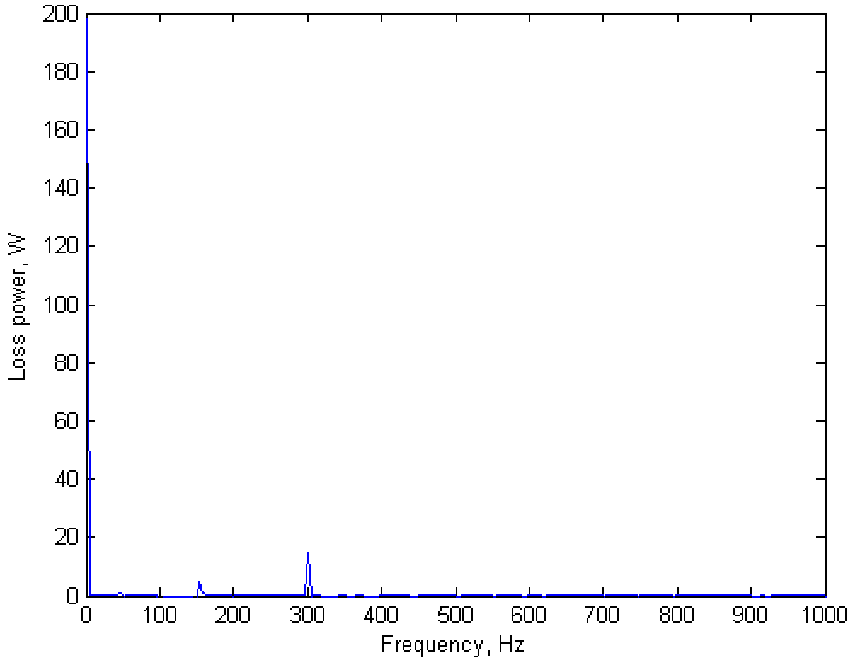


Fig. 4.15. Power loss spectrum in the DC link with 5 kW load (look errata for corrections)

The values of power losses are summarized in the Table 4.3. The share of high-frequency losses constitutes 11.5 % in total power losses, meanwhile the losses at 300 Hz comprise 6.7 % of the total power losses. As a result, the high frequency losses should be considered in system analysis.

Table 4.3. Power losses in AXMK 4x16 with 5 kW load (look errata for corrections)

Parameter	**Value**
Total power loss in cable, W	223.62
DC power losses, W	197.99
Distortion power losses, W	25.63
Power losses at 300 Hz, W	15.05
Share of high-frequency losses in total power loss, %	11.5

Dielectric losses at 300 Hz were also estimated. However, the losses are negligible and should not be taken into account.

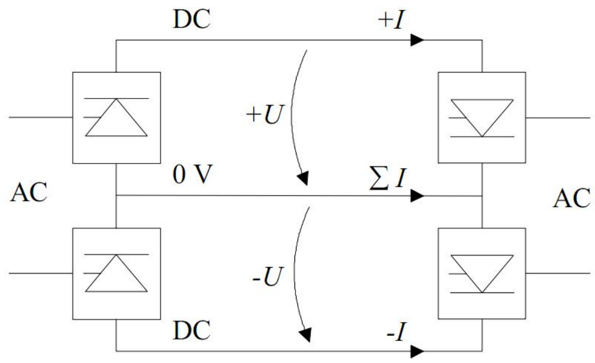


Fig.4.16. Connection concept for bipolar LVDC system (Kaipia et al., 2006)

While planning the network construction, power losses should be taken into account. The power losses for LVDC system with parallel connected neutral conductors, represented in the Figure 4.16, are calculated according to the Equation (4.19). The system is assumed to be symmetrically loaded, so the current in neutral line is equal to zero.

$$P_{\mathrm{loss}} = 2 \cdot r \cdot \left(\frac{P}{U} \right)^2 \cdot l, \tag{4.19}$$

where P is the load of one pole.

If the LVDC system has symmetrical load then the total load of the system P_{dc2} is equal to P multiplied by two. So the dependence of voltage loss of the system on total load of the system is given by the Equation (4.20).

$$P_{\mathrm{loss}} = 2 \cdot r \cdot \left(\frac{P_{\mathrm{dc2}}}{2U} \right)^2 \cdot l, \tag{4.20}$$

For instance, the Figure 4.17 shows the dependence of transmission power in LVDC on loss power for AXMK 4x35 at 65 $^{\mathrm{o}}$C with four different lengths: 1 km, 3 km, 5 km, and 7 km.

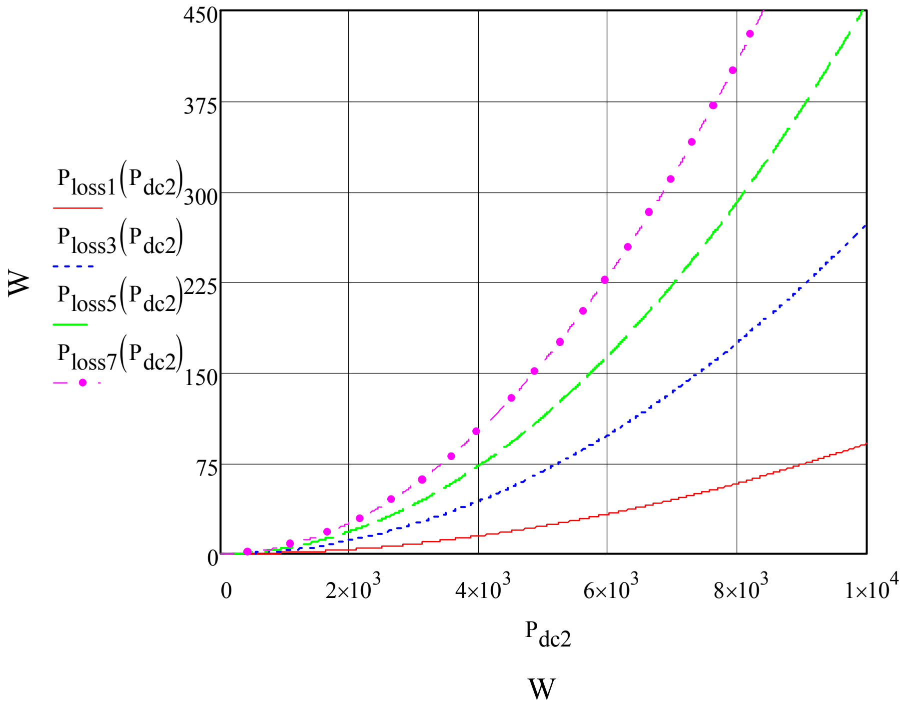


Fig.4.17 The dependence of LVDC loss power on transmission power for AXMK 4x35 at 65 ^{0}C. The numbers in sub-scripts of P_{loss} represent cable length in km

4.4 Performance of existing LV cables in LVDC system

The application of existing LV cables on direct current is allowed in cable standards. However, the cable application in LVDC and use of PLC set certain requirements. So different cable types are considered, and their suitability for these purposes is estimated.

4.4.1 Overview of studied cable types

There was a survey (Suntila, 2009) at Tampere University of Technology (TUT) concerning the suitability of existing AC cables in LVDC network. The following cables were studied: AXMK, AXCMK-HF, AMCMK, MCMK, AMKA-aerial bundle cable, and MMJ. These types of cables are described below.

One of frequently used underground cables is AXMK. AXMK is produced according to the SFS 4879. The main application is in underground power distribution systems (SFS 4879). AXMK has the following construction (SFS 4879), which is shown in the Figure 4.18:

- aluminium conductors
- XLPE-insulation
- PVC sheath

Fig.4.18 AXMK cable

The other cable for underground application is AXCMK-HF, which is produced according to the standard SFS 5546. These are power cables with special fire performance for use in power stations and sub-stations. AXCMK-HF is shown in the Figure 4.19. It is constituted from:

- aluminium conductors
- XLPE-insulation
- halogen-free polyolefin sheath
- concentric copper earth conductor (it consists of copper wires and copper contact tape, which is in contact with the wires).

Fig. 4.19. AXCMK-HF cable

AMCMK and MCMK cables are produced according to standard SFS 4880. The Figure 4.20 shows AMCMK, consisting of

- aluminium conductors
- PVC insulation
- PVC sheath
- concentric copper earth conductor

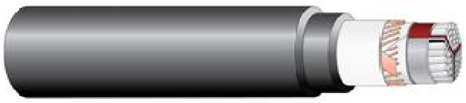


Fig.4.20 AMCMK cable

MCMK consists of the same parts as AMCMK, but it has copper conductors.

AMKA is aerial bundled cable produced according to SFS 2200 standard. The components of the cable are represented in Figure 4.21

- aluminium conductors
- PE insulation
- supporting rope, around which the insulated conductors are twisted

Fig.4.21 AMKA cable

MMJ cable is produced according SFS 2091 standard. The constituting cable parts are depicted in the Figure 4.22:

- copper conductors
- PVC insulation
- PVC sheath

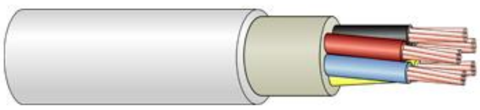


Fig. 4.22. MMJ cable

4.4.2 Suitability for LVDC power distribution

The special requirements defined by DC distribution towards cables should be considered.

A number of tests was performed on the different cables at Tampere University of Technology (Suntila, 2009). The results of the tests showed that short term durability of the cables is sufficient for DC application. In addition, the electromagnetic fields were investigated in computer simulation. As a conclusion, the strength of the field in the existing cables under DC voltage was proved not to accelerate cable degradation. So the researchers made a conclusion about suitability of existing AC cables for DC use (Suntila, 2009). However, no long term tests were performed, and it is the question of further investigation.

4.4.3 Suitability for PLC

For PLC, power cable is, actually, a transmission line. However, the cable has parameters, which are optimized for AC power transmission. Consequently, it introduces attenuation into signal transmission.

The previous research (Ahola, 2003) showed the applicability of motor cable for PLC. Likewise, LV cables are applicable for PLC in LVDC but with some limitations. For instance, the signal attenuation is decreased, when 4-conductor cable is used. If the two pairs of diagonal conductors are used for signal transmission, then some interferences are compensated. Furthermore, differential signalling is used, so common mode interferences are attenuated. The other requirement is the symmetrical construction of the cable, which provides more equal distributed cable parameters, compared with non-symmetrical one. The other limitation set by PLC is that the cable materials should provide low losses. So for insulation materials polar dielectrics, such as PVC, are not applicable. Besides, copper conductors provide low losses, but the skin-effect is more considerable in copper than in aluminium. As a result, both metals can be applied from communication point of view. Finally, AXMK and AXCMK-HF meet the above-mentioned requirements.

5 Cables for LVDC

Cable for LVDC system is a significant part of the system and it parameters should be appropriate for certain purposes. The requirements for the cable can be divided into several groups: requirements for power transmission, requirements for signal transmission, requirements concerning the effect of the cable on other parts of the system, and cost requirements. This chapter summarizes all the requirements for cable in LVDC and gives the appropriate recommendations in cable use.

5.1 Cables from power transmission point of view

For DC cable, the same factors, as for AC cables, should be considered. Rated voltage is one of the most important operating parameters for cable. The rated voltage for the cable in bipolar system is ±750 V DC.

According to requirements for solid insulation in IEC 60664-1, in case of bipolar ungrounded IT ±750 V DC system, the cable insulation should withstand 2700 V within 5 s. The long-term temporary overvoltage with duration longer than 5 s is 1750 V.

5.1.1 Recommended insulation materials and cable structure

From power transmission point of view, the cable with 4 conductors is economically preferable, because it can be used as two parallel lines. If the material of conductors is concerned, copper provides lower energy losses and voltage drop, then aluminium with the same cross-section. So from power distribution point of view, copper is better, but it is more expensive than aluminium.

The electro-magnetic fields in cable are not critical and do not set special requirements for cable in LVDC. So from power transmission point of view, the same insulation materials with the same thickness can be used, as for AC cables.

As LVDC system is ungrounded IT system, and then the concentric conductor in cable is not required from power transmission point of view.

5.1.2 Technical and economical aspects in the choice of cross-section

When choosing a cross-section of the cable different factors should be taken into account: costs, voltage drop, and required transmission capacity. All these parameters are important and should be considered simultaneously; the conductor should be both economically effective and meet certain technical requirements.
The costs, which are considered for choosing cross-section, are the construction costs and costs of losses. The losses cost constitutes part of expenses that cannot be neglected. In addition, they cause demand for extra capacity in some parts of the system.

The total expenses C of cable line consist of construction costs C_{cons} and the cost of losses $\kappa c_{\mathrm{loss},1}$ over the utilisation period, as shown in the Equation (5.1).

$$C = C_{\mathrm{cons}} + \kappa c_{\mathrm{loss},1}, \tag{5.1}$$

Capitalization factor κ can be determined according to the Equation (5.2).

$$\kappa = \psi \frac{\psi^{T} - 1}{\psi - 1}, \tag{5.2}$$

where T is the time period under consideration, assumed to be 40 years, the parameter ψ can be calculated as follows in the Equation (5.3).

$$\psi = \frac{\left(1 + \frac{r}{100}\right)^{2}}{1 + \frac{p}{100}}, \tag{5.3}$$

where r is load growth, we assume it to be 2% annually, and p is interest rate, we assume it to be 4% annually.

Cost of losses during the first year can be calculated by using the Equation (5.4).

$$c_{\text{loss}} = c\, P_{\text{loss}}\, t_{\text{h}}\,, \tag{5.4}$$

where the cost of energy losses in example calculations are c = 0.05 €/kWh, peak operating time of losses t_{h} = 2000 h, and P_{loss} stands for the power losses.

The power losses in a symmetrically loaded bipolar LVDC cable can be calculated according to the Equation (5.5), using the resistance at 65 ^{0}C from Appendix 1.

$$P_{\text{loss}} = 2 \cdot r \cdot \left(\frac{P}{U}\right)^2 \cdot l, \tag{5.5}$$

where P is load power for one pole of bipolar symmetrically loaded line, r is the resistance of the line, l is the length of the line, which is assumed to be 1 km.

Finally, after all substitutions the Equation (5.1) is transformed into Equation (5.6) for the costs of 1 km of cable line.

$$C = C_{\text{cons}} + \kappa \cdot c \cdot t_{\text{h}} \cdot 2 \cdot r \cdot \left(\frac{P}{U}\right)^2 \tag{5.6}$$

If the LVDC system has symmetrical load then the total load of the system P_{dc2} is equal to the power capacity P of one pole multiplied by two. So the dependence of voltage loss of the bipolar LVDC system on total load of the system is given by the Equation (5.7).

$$C = C_{\text{cons}} + \kappa \cdot c \cdot t_{\text{h}} \cdot 2 \cdot r \cdot \left(\frac{P}{2U}\right)^2 \tag{5.7}$$

The Figure 5.1 and 5.2 show the dependence of line costs on the power capacity for 1 km of aluminium cable symmetrically loaded in LVDC for different cross-sections. The power losses for each load can be obtained from the Figure 4.17. The cost of power losses is included in calculations.

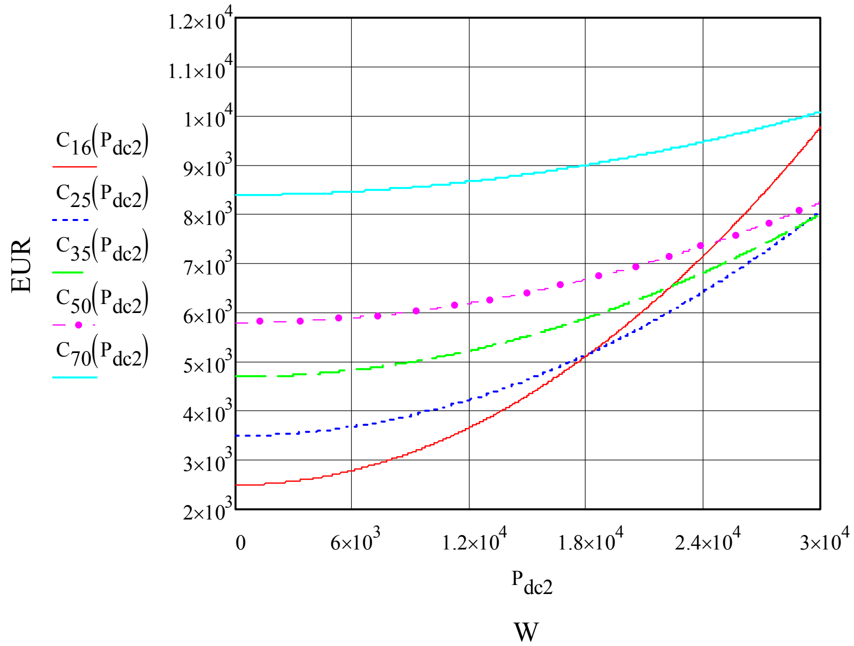


Fig.5.1. The dependence of line costs on the power capacity for 1 km aluminium conductors. The power capacity from 0 to 30 000 W. The sub-scripts of *C* represent cross-section in mm^2

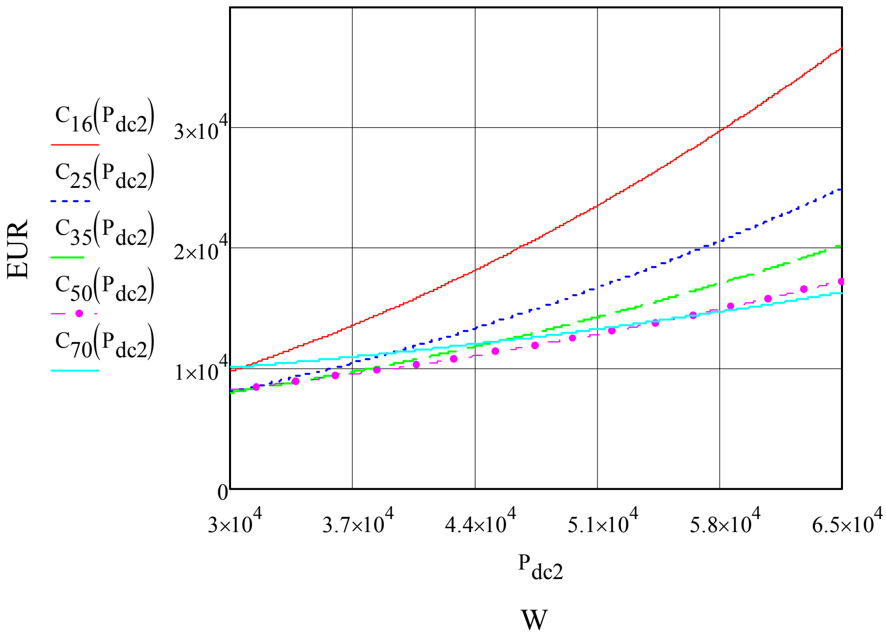


Fig.5.2. The dependence of line costs on the power capacity for 1 km aluminium conductors. The power capacity from 30 000 to 65 000 W. The sub-scripts of *C* represent cross-section in mm^2

In addition, the limiting factor for the cross section choice, which could be considered, is maximum current rating, determined by heating of cable. Table 5.1 shows, firstly, the maximum rating currents for AXMK, given in standard SFS 4879, in ground with temperature +15 ^{0}C, at depth of 0.7 m, the soil has thermal resistance of 1.0 K*m/W. Secondly, the power capacity for one pole, derived from these values at 750 V DC, is also represented. The power capacity for two symmetrically loaded poles is also given. The results show that cable has high power capacity and the maximum rating current is not a limiting factor for the cable, if low power flow is considered.

Consequently, the choice of cross-section is made according to the dependences of line costs on power capacity. For instance, if the power is higher than 18 kW then it is no longer profitable to use the cross-section 16 mm^2 and bigger cross-section should be chosen on the cable connection and parameters in the example case, considered above, for 4-conductor aluminium cables in symmetrically loaded LVDC system.

Table 5.1 Power capacity of cable, based on maximum rating current for AXMK

Cross-section of the cable, mm2	Maximum rating current for underground cable with conductor temperature +70 ^{0}C, A (SFS 4879)	Power capacity at 750 V DC for 1 pole, kW	Power capacity for 2 symmetrically loaded poles, kW
16	78	58.5	117.0
25	100	75.00	150.0
35	125	93.75	187.5
50	150	112.5	225.0
70	185	138.7	277.4

5.1.3 Condition monitoring and fault repair

A possibility to locate faults in cables using PLC is currently under consideration. Anyway, it is unlikely that cable structure affects fault locating.

If cable joints are considered, the materials of cable joints should be completely compatible with the materials of cable (Thue, 1999). Therefore, joint insulation is produced from the material with the same dielectric properties as cable insulation. Consequently, the joint insulation withstands the possible electric stresses likewise cable insulation and the same joints as for AC line can be used.

When the network structure including joints is known, the PLC enables locating discontinuations in cable insulations (fault locations), for instance, by measuring the difference in time that it takes from a transient wave caused by a fault to travel from fault location to both ends of the cable.

5.2 PLC requirements

The signal transmission yields special requirements because of the high frequency of the signal. The frequency of signal recommended by SFS 50160 varies from 3 kHz to 148,5 kHz. The research at LUT (Ahola, 2003) proved that PLC can be used at frequencies up to 30 MHz.

The losses in cable increase in cable on high frequencies both in metal and dielectric. Polar dielectrics are not used for high frequencies because of high losses and frequency dependences of dielectric parameters. So PVC cannot be used for insulation from PLC point of view. From the considered cable types the cables with XLPE insulation are appropriate.

If radio-frequency cables are considered, the non-polar conventional dielectrics are used, but the best insulation from the communication point of view is air. So different types of insulation construction are used to increase the air content in insulation, for instance, skin-foam-skin technology. However, these types of insulation are not applicable for power transmission, because of uneven structure.

If the metal of conductor is considered, then it should be mentioned, that losses in copper are lower than losses in aluminium, but skin-effect in copper is higher than in copper. As a result, both conductor materials are applicable for PLC.

From PLC, point of view concentric copper conductor can be used as a shield, reducing the high-frequency electromagnetic fields. The copper conductor should be connected to signal ground.

6 Conclusions

The main task of the thesis was to recommend the most suitable cable structure for LVDC system with PLC. The requirements, set by power transmission and possible power line communication, were studied and analyzed. As a result, the conclusions, listed below, were derived.

Firstly, from power transmission point of view the main limitation, which is set on cable selection is the cross-section selection. Different factors such as transmitted power, the line length, short-circuit currents, allowed losses, voltage drop, and economical requirements should be considered. The electro-magnetic field of LV direct current does not create any additional problems, compared with AC current.

Secondly, PLC application gives its limitations, mainly on cable materials.
The insulation material should be non-polar dielectric, because of high frequency signal of PLC. For LVDC power the most suitable is XLPE.

Thirdly, as the LVDC system is IT system, no concentric conductor is required. However it can be used as a shield from PLC point of view and for preventing the cable from operating as an antenna for high frequency interferences caused by the inverters.

Fourthly, the cable jacket should have enough mechanical properties for ploughing. The recommendations of cable standards for line construction should be fulfilled. The PE jacket has suitable mechanical properties. Cables with PVC jacket can also be used. Both materials have sufficient moisture resistance. However, during exploitation PVC becomes less resistant to low temperatures and to moisture, than at the beginning of exploitation.

Finally, despite the differences between conditions created in AC and DC distribution system, the existing AC cables can be used in LVDC. Although special requirements should be considered and appropriate cable should be chosen. However, long-term operation of cables in these conditions was not investigated. So the research of cable lifetime should be done in future work.

References

ABB, 2008. Technical description of HVDC Light® technology. [Available on-line at www.abb.com accessed February 2010]

Ahola, J., 2003. Applicability of Power-Line Communications to Data Transfer of On-Line Condition Monitoring of Electrical Drives. Lappeenrannan teknillinen yliopisto, Lappeenranta, ISBN 951-764-783-2.

Anders, G.J., 2005. Rating of Electric Power Cables in Unfavorable Thermal Environment. Wiley-IEEE Press, 2005, 326 p.

Arrillaga, J., 1998. High Voltage Direct Current Transmission. 2nd edition. The Institution of Electrical Engineers, London, 1998, 311 p.

Baran, M.E. and Mahajan, N.R., 2003. DC Distribution for Industrial Systems: Opportunities and Challenges. *Industry Applications, IEEE Transactions on,* 39 (6), November-December 2003, 1596 – 1601.

Belorussov N.I. and Grodnev I.I., 1959. Radiofrequency cables. Second edition. State Power Engineering Publishing House, Moscow. [in Russian]

Borealis AG, 2008. Extruded Insulation System for HVDC Cables is a proven High Performance Reality. [Available on-line at http://www.borealisgroup.com/ accessed February 2010]

Borioli, E., M. Brenna, R. Faranda, and G. Simioli, 2004. Comparison between the Electrical Capabilities of the Cables Used in LV AC and DC Power Lines. *2004 11th International Conference on Harmonics and Quality of Power, September 12-15, 2004.*

Brown, P.A., 1999. Power Line Communications – Past, Present and Future. *The International Symposium on Power Line Communications (ISPLC), 30 March - 1 April 1999, Lancaster, UK.* [Available online at http://www.isplc.org/]

Konaté, C.; Kosonen, A.; Ahola, J.; Machmoum, M.; and Diouris, J.-F., 2010. Power line communication in motor cables of inverter-fed electric drives. *IEEE Transactions on power delivery*, vol. 25, no.1, January 2010.

Draka NK Cables Ltd., "Power Cables, 1 kV Aluminium", Draka NK Cables Ltd. web-site http://www.draka.com/draka/Countries/Draka_Finland, accessed April, 2010.

EN 50065-1, 1991. Signalling on Low Voltage Electrical Installations in the Frequency Range 3 kHz to 148.5 kHz. *CENELEC*, Brussels, Belgium, 1991.

Galli, S. and Logvinov, O., 2008. Recent Developments in the Standardization of Power Line Communications within the IEEE. *IEEE Communications Magazine,* July 2008.

Grigsby, Leonard L., ed. *Electric Power Generation, Transmission, and Distribution.* Boca Raton: CRC Press Taylor&Francis Group, 2007.

HomePlug Power Alliance, Homeplug 1.0 Technology White Paper, HomePlug Power Alliance Web site, http://www.homeplug.org/tech/whitepapers/, accessed March 2010.

Homeplug Power Alliance, 2010. IEEE Publishes 1901 Draft Standard for Powerline Communications (Press release). HomePlug Power Alliance Web site, http://www.homeplug.org/news/ accessed May 2010.

IEC 60502-1. Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) - Part 1: Cables for rated voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um = 3,6 kV).

IEC 60664-1. Insulation coordination for equipment within low-voltage systems - Part 1: Principles, requirements and tests.

Jensen, M.H. and Bak-Jensen, B., 2001. Shunt admittance of the four-wire distribution cable with sector-shaped conductors. *2001 IEEE Porto Power Tech Proceedings*, 10-13 September, Porto, Portugal.

Kaipia, T., 2009. Revolutionary Electricity Distribution System Based on Power Electronics. Power Electronics in Electricity Distribution. Academy of Finland, Annual Seminar 2009. [Available on-line at www.aka.fi accessed January 2010]

Kaipia, T.; Salonen, P.; Lassila, J.; and Partanen, J., 2006. Possibilities of Low Voltage DC Distribution Systems. *Nordic Distribution Automation Conference (Nordac).* 21-22 August, 2006, Stockholm, Sweden.

Korshun, S., 2009. Dimensioning DC-voltage capacitor for a DC-distribution system and dynamic analysis. Master of Science thesis. Lappeenranta University of Technology, 2009.

Kosonen, 2008. Power line communication in motor cables of variable-speed electric drives – analysis and implementation. Lappeenrannan teknillinen yliopisto, Lappeenranta, ISBN 978-952-214-641-0.

Kurohane, K.; Senjyu, T.; Yonaha, Y.; Yona, A.; Funabashi, T.; and Chul-Hwan Kim, 2009. A Distributed DC Power System in an Isolated Island. *IEEE International Symposium on Industrial Electronics (ISIE), 5-8 July 2009.*

Lakervi, E. and Holmes, E.J., 1998. Electricity distribution network design. 2nd edition. Peter Peregrinus Ltd., on behalf of The Institution of Electrical Engineers, London, United Kingdom.

Lakervi, E. and Partanen, J., 2008. Sähkönjakelutekniikka (Electricity Distribution Technology). Gaudeamus Helsinki University Press. Helsinki, 2008.

Lassila, J.; Kaipia, T.; Voutilainen, V.; Koivuranta, K.; Haakana, J.; and Partanen, J., 2008. *Potential of Power Electronics in Electricity Distribution Systems*, 23-24 June 2008, Frankfurt.

Maruyama, S.; Ishii, N.; Shimada, M.; Kojima, S.; Kojima, S.; Tanaka, H.; Asano, M., Yamanaka, T.; and Kawakami, S., 2004. Development of a 500-kV DC XLPE Cable System. Furukawa Review No.25 (March 2004). [Available on-line at http://www.furukawa.co.jp/review/fr025.htm accessed Febuary 2010]

Matsumoto Y. and Yanabu S. , 2004. A Vision of an Electric Power Architecture for the Next Generation. *Electrical Engineering in Japan,* 150 (1), 18-25.

Mohan, N.; Undeland, T.M.; and Robbins W.P., 2003. Power Electronics. Converters, Applications and Design. John Wiley & Sons., Inc., USA.

Mugala, G.; Eriksson, R.; and Pettersson, P., 2006. Comparing Two Measurement Techniques for High Frequency Characterization of Power Cable Semiconducting and Insulating Materials. *IEEE Transactions on Dielectrics and Electrical Insulation.* Volume: 13 , Issue: 4, 712 – 716.

Nilsson D. and Sannino A., 2004. Efficiency analysis of low- and medium-voltage dc distribution systems. *2004 IEEE Power Engineering Society General Meeting. IEEE, 10 June 2004.*

Nuutinen, P.; Salonen, P.; Peltoniemi, P.; and Silventonen, P., 2008. Customer-End Inverter in an LVDC Distribution Network. *Proceedings of Nordic Workshop on Power and Industrial Electronics*, 2008.

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. and Paajanen P. (LUT); Järventausta, P., Tuusa, H., Suntio, T., Nikander, A., Kannus, K., Lahti, K., Mäkinen, A., Alahuhtala, J., Suntila, T., Nousiainen, L., Rekola J. and Vornanen, T. (TUT), 2010. Research report: Power Electronics in Electricity Distribution, part 2/2. Lappeenranta University of Technology, Tampere University of Technology, May 2010.

Salonen, P. , Kaipia, T., Nuutinen, P., Peltoniemi, P., and Partanen, J., 2008a. An LVDC Distribution System Concept. *NORPIE Nordic Workshop on Power and Industrial Electroncis (2008).*

Salonen, P. , Kaipia, T., Nuutinen, P., Peltoniemi, P., and Partanen, J., 2008b. Fault Analysis of LVDC Distribution System. *International World Energy System Conference (WESC 2008)*, June 30 – July 2, 2008, Iasi, Romania.

Salonen, P. Nuutinen, P., Peltoniemi, P., and Partanen, J., 2009. Protection scheme for an LVDC distribution system. *20th International Conference and Exhibition on Electricity Distribution, 8-11 June 2009.*

Seki, A.; Miyamoto, S.; Okitani, A.; Ohki, Y.; Sakuma, S.; Fukuyama, S.; and Miyauchi, H., 1994. Insulation Characteristics of XLPE Cables and their Accessories for High Frequency Voltage with PWM Inverter. *Transmission and Distribution Conference, 560 – 566, 10 - 15 April 1994, Chicago, IL.*

SFS 2091, 1998. Asennuskaapelit: Muovivaippakaapeli MMJ. Suomen standardisoimisliitto. 9 s.

SFS 2200, 2005. 0,6/1 kV kaapelit: Riippukierrekaapeli AMKA. Suomen standardisoimisliitto. 7 s.

SFS 4879, 1995. 0,6/1 kV Power cables. XLPE-insulated Al- and Cu-cables. Ratings and Guide to use. (0,6/1 KV Voimakaapelit. PEX-eristeiset Al- ja Cu-johtimiset kaapelit. Mitoitus ja käyttöohje). Suomen standardisoimisliitto. 30 s.

SFS 4880, 1995. 0,6/1 kV voimakaapelit: PVC-eristeiset ja –vaippaiset kaapelit, rakenne ja testaus. Suomen standardisoimisliitto. 31 s.

SFS 5546. 1995. 0,6/1 kV voimakaapelit: Halogeenittomat nippuna itsestään sammuvat kaapelit, rakenne ja testaus. Suomen standardisoimisliitto. 37 s.

Starke, M.R.; Tolbert, L.M.; and Ozpineci, B., 2008. AC vs. DC Distribution: A Loss Comparison. *2008 Transmission and Distribution Conference and Exposition, 21-24 April 2008, Chicago, IL.*

Suntila, T., 2009. Pienjännitekaapeleiden soveltuvuus sähkönjakeluun tasajännitteellä (Suitability of low voltage power cables for distribution of electricity at direct-current operating voltage). Master of Science Thesis (in Finnish). Tampere University of Technology.

Thue, William A., ed., 1999. Electrical Power Cable Engineering. Marcel Dekker, Inc., 1999.

Wagenaars, P.; Wouters, P.A.A.F.; Wielen, P.C.J.M.; and Steennis, E.F., 2008. Estimation of Transmission Line Parameters for Single-Core XLPE Cables. *2008 International Conference on Condition Monitoring and Diagnostics*, 21-24 April 2008, Beijing.

Whitaker, Jerry C., 1999. AC Power Systems Handbook. Second Edition. Boca Raton: CRC Press LLC, 1999.

Appendix 1. Calculation of voltage drop and line costs dependences on the power capacity

The voltage drop of a single pole of a bipolar LVDC system during symmetrical loading in the simplest case is given in equation (1.1).

$$U_d = r \cdot I \cdot l \, , \tag{1.1}$$

where r is the pole resistance of the cable per km, l the length of the cable in km's, and I the pole current.

The dependence of voltage drop on power demand P is obtained by substituting the current as a function of receiving end node voltage, U (750 V) and power demand (P) of a single pole:

$$U_d = r \cdot \frac{P}{U} \cdot l \tag{1.2}$$

The resistances of cables are represented in table 1.2

Table 1.2 The resistances of AXMK-cables at the temperature +20 ^{0}C

Cross-section of the cable, mm^2	DC phase conductor resistance at +20 ^{0}C, Ω/km	DC resistance at +65 ^{0}C, Ω/km
4x16	1.91	2.26
4x25	1.2	1.42
4x35	0.868	1.03
4x50	0.641	0.76
4x70	0.443	0.52

The resistances at +65 ^{0}C are calculated according to the Equation (1.3)

$$R = R_{20}\,(1 + \alpha(T - T_o)), \tag{1.3}$$

where R_{20} is the resistance at 20 ^{0}C, T_0 is reference temperature (20 ^{0}C), α is temperature coefficient, which is 4.03x10^{-3} 1/^{0}C for aluminium at 20 ^{0}C (Anders, 2005).

The voltage drop in per cents is defined by the Equation 1.4.

$$U_{\mathrm{d}} = r \cdot \frac{P}{U \cdot U_{\mathrm{N}}} \cdot l \, , \tag{1.4}$$

where U_{N} is rated voltage for the system.

The resistance of a DC pole depends on the selected conductor cross-sections but also on the connection concept of the DC system. For a unipolar DC line, the resistance is defined by the Equation (1.5) (Kaipia, 2008):

$$r_{\mathrm{UP}} = r_1 + r_2 = \frac{1}{\sum\limits_{\mathrm{i=n}} \frac{1}{r_{1\mathrm{i}}}} + \frac{1}{\sum\limits_{\mathrm{i=n}} \frac{1}{r_{2\mathrm{i}}}} \, , \tag{1.5}$$

where r is the resistance of DC cable, UP stands for unipolar system, r_1 is the resistance of first pole single conductor, r_2 is the resistance of the second pole single conductor, and n is the number of parallel conductors.

Respectively for a bipolar line, we can write the Equation (1.6) when the line is symmetrically loaded. In the case of asymmetric loading also the resistance of neutral wire has to be taken into account (Kaipia 2008).

$$r_{\mathrm{BP}} = \frac{1}{\sum\limits_{\mathrm{i=n}} \frac{1}{r_{\mathrm{i}}}} \, , \tag{1.6}$$

where BP stands for bipolar system.

As an example, the dependence of voltage drop in cable AXMK 4x35 on length was calculated for one pole of bipolar system for different transmission power. In addition, the neutral conductors are parallel connected as it is shown in Figure 1.1. The obtained dependences are shown in the Figure 1.1.

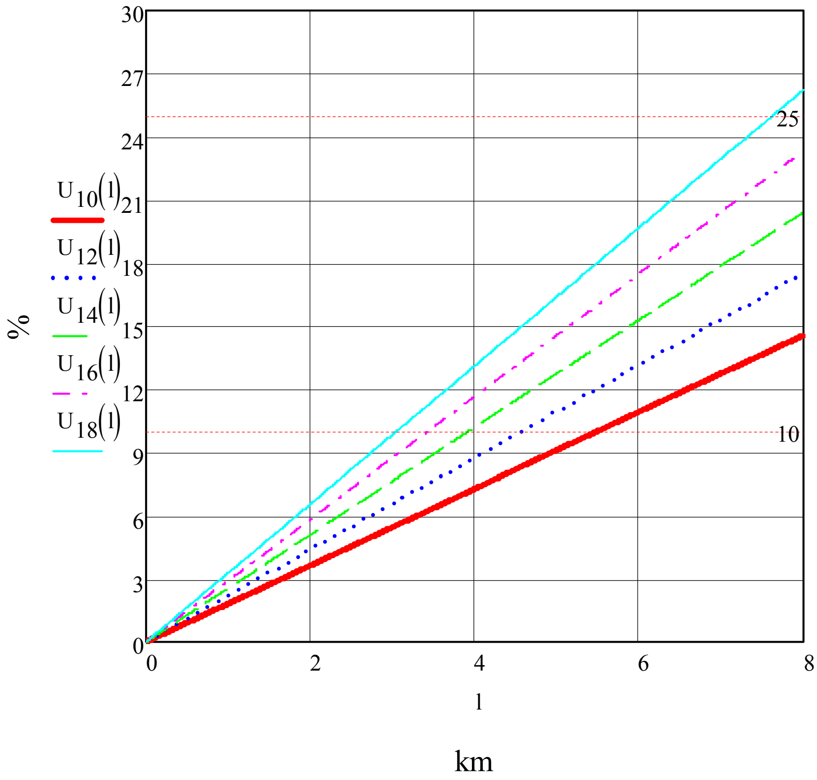


Fig.1.1. The dependence of voltage drop on cable length for AXMK 4x35 at 65 ^{0}C. The sub-indexes of voltage drop show the power of load in kW

The dependence of voltage drop in per cents on the power capacity for different cross-sections is represented in the Figure 1.1. The cross section is indicated by sub-indexes.

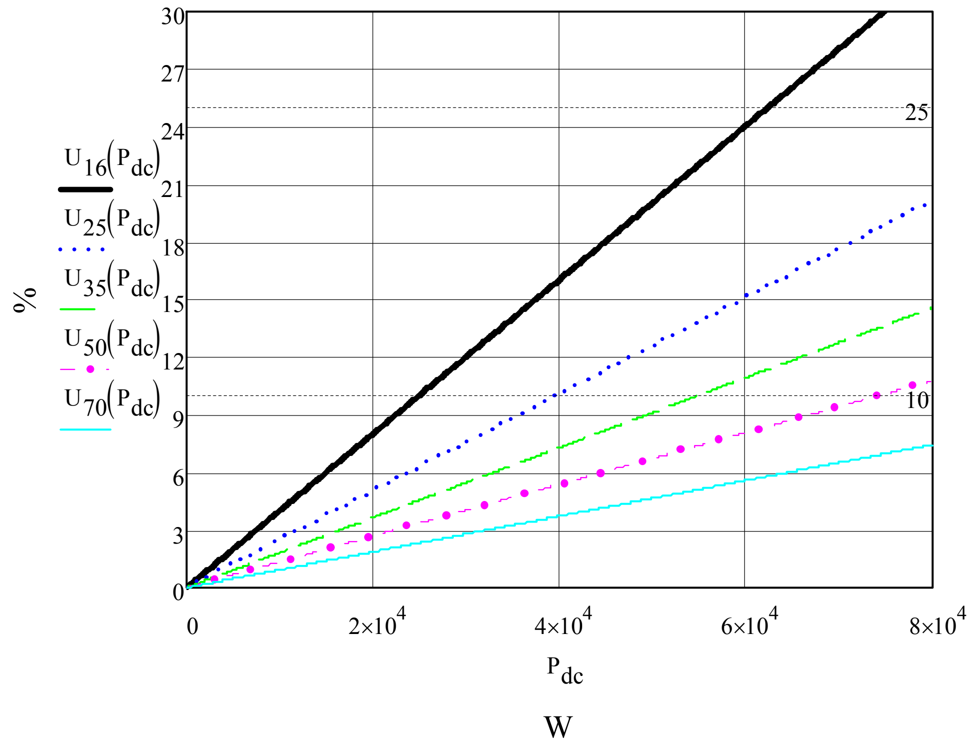


Fig.1.2. The dependence of voltage drop in Al cable conductors at 65 ^{0}C with different cross-sections in per cents on power capacity. The sub-scripts of U represent cross-section in mm^2

Construction costs for cable lines used in example calculations are as shown in the table 1.1.

Table 1.1. Construction costs for 4 conductor low voltage underground cables.

Cross-section, mm^2	Construction cost, €/km
16	2500
25	3500
35	4700
50	5800
70	8400
95	9200
120	11200
150	13400
185	14800
240	20900
300	26300

The total expenses of cable line consist of construction costs C_{cons} and the cost of losses $\kappa c_{loss,1}$ over the utilisation period, as shown in the equation (1.7).

$$C = C_{cons} + \kappa c_{loss,1}, \tag{1.7}$$

The example calculations presented here will be made for 1 km of cable.

Capitalization factor κ can be determined according to the Equation (1.8).

$$\kappa = \psi \frac{\psi^T - 1}{\psi - 1}, \tag{1.8}$$

where T is the time period under consideration. We assume it to be 40 years. Where ψ can be calculated according to the Equation (1.9).

$$\psi = \frac{\left(1 + \frac{r}{100}\right)^2}{1 + \frac{p}{100}}, \tag{1.9}$$

where r is load growth, we assume it to be 2% annually, and p is interest rate, we assume it to be 4% annually.

So we get the value ψ = 1.00385 and κ = 40.32.

Cost of losses during the first year can be calculated by using the Equation (1.10).

$$c_{loss} = c\, P_{loss}\, t_h, \tag{1.10}$$

where the cost of energy losses in example calculations are c = 0.05 €/kWh, peak operating time of losses t_h = 2000 h, and P_{loss} stand for the power losses.

The power losses in a symmetrically loaded bipolar LVDC cable can be calculated according to the Equation (1.11), using the resistance at 65 ^{0}C.

$$P_{\mathrm{loss}} = 2 \cdot r \cdot \left(\frac{P}{U} \right)^2 \cdot l \tag{1.11}$$

Finally, after all substitutions the Equation (1.7) is transformed into Equation (1.12) for the costs of 1 km of cable line.

$$C = C_{\mathrm{cons}} + \kappa \cdot c \cdot t_{\mathrm{h}} \cdot 2 \cdot r \cdot \left(\frac{P}{U} \right)^2 \tag{1.12}$$

If the LVDC system has symmetrical load then the total load of the system P_{dc2} is equal to the power P of one pole multiplied by two. So the dependence of voltage loss of the system on total load of the system is given by the Equation (1.13).

$$C = C_{\mathrm{cons}} + \kappa \cdot c \cdot t_{\mathrm{h}} \cdot 2 \cdot r \cdot \left(\frac{P}{2U} \right)^2 \tag{1.13}$$

Figure 1.2 presents dependences of line costs on the power demand for different cable cross-sections of bipolar LVDC line on transmission powers from 0 to 20 kW. The cross-sections in mm^2 are represented by sub-indexes of costs. Figure 1.3 shows the line costs on transmission powers from 30 to 65 kW.

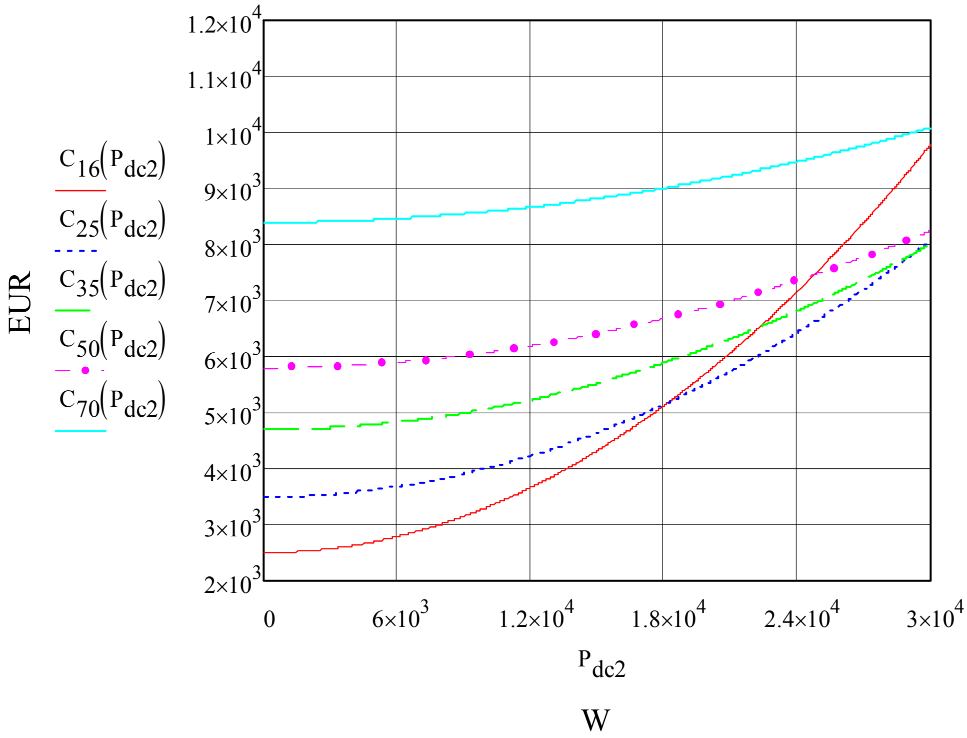


Fig.1.3. The dependence of line costs on the power capacity for 1 km aluminum conductors. The power capacity from 0 to 30 000 W. The sub-scripts of C represent cross-section in mm^2

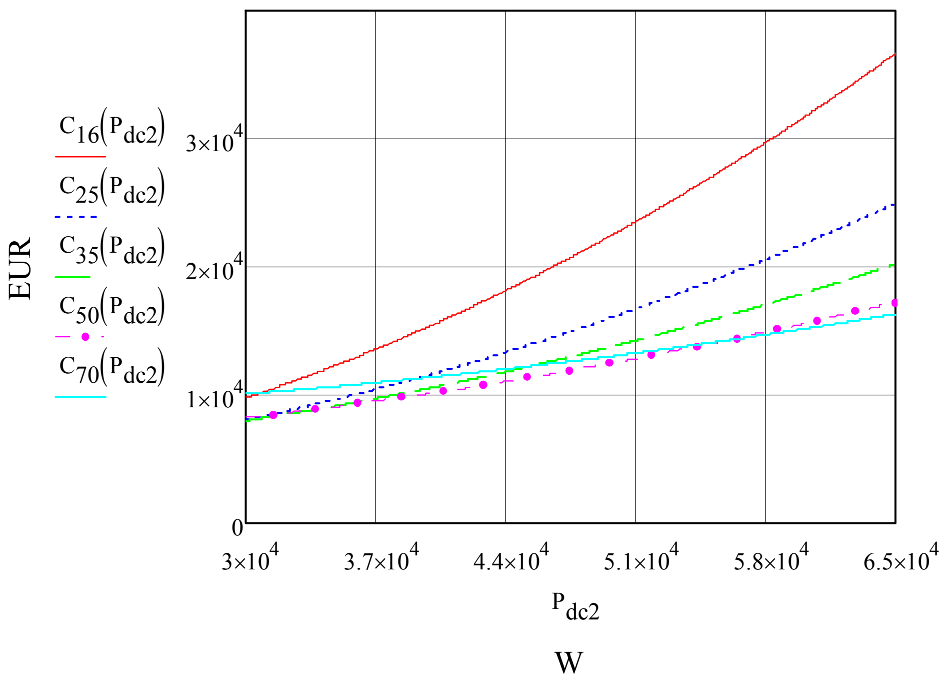


Fig.1.4. The dependence of line costs on the power capacity for 1 km aluminium conductors. The power capacity from 30 000 to 65 000 W. The sub-scripts of C represent cross-section in mm^2