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The Development and Assessment of HVAC Cable Models for Electrical Transmission Network Planning Studies

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been previously submitted for doctoral or equivalent academic degree.
Triin Kangro

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signature

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Kõrgepingeliste kaabelliinide mudelite arendamine ja analüüs elektrivõrgu planeerimisülesannete raamistikus

TRIIN KANGRO

TTÜ KIRJASTUS

Contents

List of Publications

A list of author's publications, on the basis of which the thesis has been prepared:

I T. Kangro, J. Kilter, J. De Silva, "Comparative Analysis of HVAC Cable Metallic Sheath Modelling Approaches for Network Studies," *IEEE 18th International Conference on Harmonics and Quality of Power (ICHQP18*), Ljubljana, Slovenia, May 2018.

II T. Kangro and J. Kilter, "Analysis of Transmission Network Shot Cable Line Sheath Bonding Methods," *IEEE* 18th *International Conference of Environment and Electrical Engineering (IEEE EEEIC) and IEEE 2nd Industrial and Commercial Power Systems Europe (I&CPS Europe)*, Palermo, Italy, June 2018.

III T. Kangro, J. Kilter, J. De Silva, K. Tuttelberg, "Assessment of HV XLPE Cable Sheath Layer Modelling Approaches for EMT Studies," *IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, Riga, Latvia, November 2018.

Author’s Contribution to the Publications

The author of the thesis is the main author of all included publications. The author developed and implemented all of the solutions being presented and wrote all of the papers.

Publication I presents an analysis of the cable line sheath layer and the developed cable sheath layer modelling approaches for network studies. The author applied all of the various modelling approaches, and analysed the results with a focus on variations that appeared during the course of network operations. The author modelled a transmission network area and analysed the extent of the network modelling area for mixed networks. To date a comparison between the sheath modelling methods being used has not been conducted, and there was no clear understanding regarding the impact of the use of the sheath modelling method on the network study results.

Publication II analyses the sheath voltage and current levels in the cable line part of the transmission network. The author presents sheath voltages and currents using as an example the Estonian transmission network. As far as the author is aware, this is the first work at the transmission system level which focuses so deeply on cable sheath voltage and current values, and which provides a comparison between the two most-often implemented sheath bonding methods with an analysis of the optimum number of cross-bonding sections. The results that are provided in this publication are particularly valuable for transmission system operators in the network planning process.

Publication III demonstrates various modelling approaches with frequency-dependent sheath impedance characteristics. The author provides the single layer approach together with the equivalent single layer and double layer sheath approaches, as well as presenting those differences which appeared in terms of impedance characteristics in the frequency domain, and analyses the effect on the network study results. The presentation and analysis of cable sheath impedance characteristics has not previously been published. It provides more clarity regarding the various cable sheath modelling methods.

Abbreviations and Symbols

ρ	Resistivity
A_C	Cross-section area
C	Capacitance
I	Current
Q	Reactive power
r	Radius
V	Voltage
AC	Alternating current
CB	Cross-bonding
DC	Direct current
EHV	Extra high voltage
EMF	Electromagnetic field
EMT	Electromagnetic transient
EMTDC	Electromagnetic transients including DC
EMTP	EMT-based program
EPR	Earth potential rise
EQ	Equivalent
FACTS	Flexible AC transmission system
FD	Frequency dependent
FFO	Fast-front overvoltage
GCC	Ground continuity conductor
HPFF	High pressure fluid filled
HPGF	High pressure gas filled
HV	High voltage
HVAC	High voltage alternating current
OHL	Overhead line
PSCAD	Power Systems Computer Aided Design
PSS/E	Power System Simulator for Engineering
RE	Receiving end
RMS	Root mean square
SCFF	Self-contained fluid filled
SE	Sending end
SFO	Slow-front overvoltage
SIWV	Switching impulse withstand voltage
SVL	Sheath voltage limiter
TOV	Temporary overvoltage
TSO	Transmission system operator
UG	Underground
VFFO	Very-fast-front overvoltage
VT	Voltage transformer
XLPE	Cross-linked polyethylene

Introduction

Background

The traditional method for transferring electrical power across a network has been the use of overhead lines (OHLs). In the very near future there is a good chance of significant changes taking place, with the domination of OHLs in the transmission network possibly being taken over by underground (UG) cable lines. The date of laying the first UG cable line can be arguable, but the history of this form of electrical distribution reaches back to the 1880s [1]-[2]. So far, UG cable line installation has found more application in the distribution network. Nevertheless, the focus for constructing UG cable lines is increasingly shifting to transmission networks. The drive to replace conventional OHLs with UG cable lines and laying new transmission lines as UG cable lines is being generated by a good many aspects. This includes growing population density and urbanisation, with the concomitant visual impact that OHLs have. There are also environmental and technical considerations that favour UG cable lines, such as space constraints, or crossing rivers or the sea. In European countries, due to the existing electricity markets, more reliable interconnections are needed between transmission network regions. In contrast, in North America and other parts of the world the growing number of natural disasters is leading governments and transmission system operators (TSO) to favour UG cable installations [3]. The growing demand for renewable energy has also had an impact, since wind power plants are often connected to the system through cable lines. Evolution in cable line installation is also supported by breakthroughs in material science and development work that is being carried out by cable manufacturers. Several TSOs are looking into future proposals in which HV transmission lines could be constructed as UG cable lines and existing OHLs could be replaced by UG cable lines [3]-[7]. Leading countries in this movement are Denmark, the Netherlands, and Germany. The statistics regarding installed cable lines lengths in transmission networks can be found in [2] and [8]. Newer statistic on this topic could not be found in the available literature.

Besides the transition to cable networks, transmission networks are having to face up to rapid changes and constant development, now more than ever before. Electrical systems are becoming more complex, partially because they are using new and not-so-well-understood technologies and network components (such as power electronic devices). Interaction between various network components may affect the operational aspects of the system. The load characteristics in the system are also undergoing a process of change, where the variations are taking place ever more rapidly and in greater magnitudes. One of the most concerning factors in terms of future electrical networks is the increasing number of power electronic (PE) devices. Their use will lead to changes in system characteristics and inertia, resulting in issues which may be related to network stability, possible resonances, and harmonics [9]. Transmission network characteristics and operational concepts are in a process of constant change. The question becomes how to provide system reliability and optimum management, and to make cost-effective planning decisions while considering the network's existing and future characteristics, changes in transition period, and any new operational aspects in terms of network components. Any understanding of this new situation in terms of transmission networks is essential from the system operations and planning point of view.

Complex networks raise the demand for network modelling and analysis. A number of TSOs have also come to this conclusion, seeing the increasing need for network simulation models, especially when planning new transmission lines and connecting new devices and loads into the network. However, this will raise other questions that need to be resolved. Modelling a complex network and composing detailed models for system studies becomes a highly challenging process, and one which is time-consuming and mathematically burdensome. At the same time, network components become ever-more sensitive, requiring more detailed and comprehensive modelling. The number of phenomena that need to be studied also increases, due to new components being installed and so-far-unidentified phenomena in networks. In order to be able to achieve sufficient accuracy level in the results, the composed models tend to be voluminous in terms of data and with a high level of detail contained within them. There are limitations on the available data, as well as in computational capacity. Therefore it is crucial to be able to gain clarity and a general understanding when it comes to composing models for future network studies.

Cable Line Studies

Constructing cable lines is no longer a new practice. However, the cable field is constantly developing and been improved. Therefore cable lines are increasingly finding more use at higher voltage levels, being used more in complex systems, and taking a wider share of the load in modern networks. When it comes to modelling cable lines there are still a high number of shortcomings that need to be solved, especially when considering the characteristics of future networks. Based on the analysis that is available in the current literature the main shortcomings have to date included the following points:

- The lack of availability of published analysis in terms of transmission networks
- An analysis which is specific only for certain cable links (with a specific configuration and length)
- There is no general overview available of cable sheath modelling principles
- No analysis of cable sheath data representation and approximations for time domain electromagnetic transient (EMT) modelling is available
- No analysis is available regarding the cable sheath approximation effect in network studies
- There seems to be no available published analysis of cable sheath voltage and current levels in transmission networks
- Any effectiveness of cable line installation method for short cable lines
- An analysis of the optimum number of cross-bonding points along the cable line
- An analysis which is related to mixed lines and mixed networks

Until now cable lines have been more common in distribution networks. Therefore the majority of research has dealt with cable lines at the distribution network level. An increased level of wind power developments and interconnections between transmission networks has focused a need for cable line studies even at the transmission network level. The general principles for cable line modelling at high voltage levels can be found in several areas of research [5]-[6], [10]-[11]. The research that has been carried out at the transmission level has been led by European countries (such as Denmark [5]-[6] and the Netherlands [12]), and which consider going over to cable networks at the transmission system level. The potential for routing electricity networks underground in Europe has been discussed in [13] and [14]. The general impact of UG cables on power networks is reported in [15]. Until now, those studies which focus on cable modelling are characterised as having observed one specific long cable line or connection, with its specific installation method and operational characteristics. When it comes to the interest of meshed, urban cable networks at the transmission level with relatively short cable lines, any previously published research which covers this field is unavailable.

Cable modelling is complex, due to the cable layered structure and the mutual interaction between the layers. In addition, the parameters are frequency dependent and characteristics distributed by nature. When analysing transient phenomena, consideration has to be paid to the wave propagation theory in multiconductor systems [16]-[17]. The method that is based on the wave propagation theory was introduced quite a long time ago in [18]-[19]. In time, the conclusion has been reached that the complex cable layout needs to be represented more precisely, especially for transient analysis. Therefore, developments in cable modelling principles are needed.

Previously, a great deal of work has been carried out in the field of mathematical modelling for cables. Cable system impedance and admittance throughout the representation of transient studies can be found, such as in [1], [17], [20]-[22]. For time domain modelling in EMT, various modelling models have been developed over time and these are introduced variously, such as in [23]. Several areas of research focus on determining the proper modelling model for cable line studies [24]-[27]. Recommendations which have been made by the Cigre working group can be found in [23].

One concern that has been reported is accurate data representation in the cable model, due to the complex cable structure and data which is often unavailable. Accurate geometry and the material properties of conductive (core and sheath), insulating, and semi-conductive layer representation in the cable model can become challenging. For network studies, it is common to implement certain simplifications in cable layered structure and parametric values. However, for transient studies, the approximations that have been made can lead to inaccurate study results. Cable data representation can be found in a number of previously-conducted works, such as [28]-[29]. It has been found that the cable insulation semi-conductive layer has a high level of importance in simulation results. There are studies that focus on the influence of the semi-conductive layer representation in cable model, such as [30]-[32]. When it comes to modelling the complex sheath layer, there is no clear understanding being presented in the available literature. In commercial EMT-based programs (EMTP) the cable sheath cannot yet be presented as a complex layer which is composed of two different conductive materials. Thanks to this, simplifications are needed in sheath layer representation. Based on the available literature, [2], [5]-[6], [28], [33]-[36], there are some approaches for sheath parameters and sheath layer representation in EMTP. However, it is not clear how these simplifications and approximations in cable sheathing may affect the network study results.

In addition to challenges that are raised by cable sheath modelling, another concern is the induced voltages and circulating currents in cable sheathing. When compared to conventional OHLs, this is a new concern from the line operations and installation side of the subject. Too high an induced voltage in the sheath layer poses a safety hazard for both personnel and line operations. While too high a circulating current in the sheath layer decreases the line’s current carrying capability. Several cable sheath bonding methods have been developed to deal with these issues. Cable line sheath bonding and grounding methods are introduced in various areas of available literature, such as [17], [37]-[38]. When planning a cable line installation, it may become challenging when it comes to making the right choice over the cable installation method to be used, especially when there is no clear regulation regarding allowable induced voltage levels in the sheath layer by the TSO. The investment that is needed for cable line installation is directly related to the bonding method. Few previously-conducted analyses can be found that observes voltage and current values in the cable sheath layer, such as [39]-[40]. However, these studies deal with medium voltage, long cable lines which are directly connected to wind parks. In [41], the sheath voltages and currents are also observed in a cross-bonded, medium voltage cable line, in respect to various modelling model comparisons with different cable arrangements. No studies can be found at the transmission system level which observe voltage and current levels in the cable sheath. Furthermore, no previous studies analyse the optimum number of cross-bonding points when the special sheath bonding method is implemented. One additional aspect to consider is that including special bonding methods in EMT modelling causes a decrease in the simulation time step, which makes the modelling of cross-bonded cable lines challenging.

When transitioning from OHL networks to cable networks, TSOs are faced with mixed networks and mixed lines. In a mixed line, where the transmission line is composed partly of OHLs and partly by cable lines, new phenomena appear and need to be critically analysed as early as the network planning stage. So far, this is still an under-investigated area. Some concerns which are related to mixed lines are discussed in [1]. For mixed lines, overvoltages which originate from lightning and switching transients that are commonly not inherent for cable lines become a concern. Some specific transient studies have been carried out in [42]-[44]. However, these studies deal with long lines, where there is a higher damping in overvoltages than in the case of short line lengths. Other specific studies which deal with mixed lines can be found in [45]-[47]. The mixed line situation can last for long periods of time in a network, until all of the OHLs have been replaced. For some transmission lines, operating them permanently as mixed lines may be necessary and even unavoidable. Mixed networks are definitely an area that require future research and analysis. In general, when a cable line installation is being planned, each project needs to be analysed on a case-by-case basis. No generalisations should be made or principles taken from previous project cases.

The Objectives of the Thesis

Cable line electrical properties and operational characteristics differ from those of conventional OHLs. In considering the latest developments in electrical networks and the future perspective of UG cable lines, transmission networks are changing to become mixed networks or entirely cable networks.

Research interest is shifting from specific interconnecting long cable line connections over to meshed networks which contain many rather short UG cable lines. These networks are characteristic of urban areas (urban networks). This raises the need to analyse cable networks from the TSO point of view and requires guidelines for planning, designing, and operational aspects.

The initiative for this thesis was the Estonian TSO, Elering, which showed an interest in changing over from conventional OHLs to UG cable lines in urban areas. Several HV transmission lines have reached the end of their life expectancy and need to be replaced. There are several new transmission lines that have been planned for the network. In Estonia’s urban areas, the TSO preference is to install UG cable lines. The current network configuration already includes some HVAC UG cable lines (with installation included both ends bonded and cross-bonded), along with mixed lines. However, their proportion is rather low and, therefore, no comprehensive analysis has been carried out until now. The TSO has limited practice and understanding in UG cable installation methods in regard to what kind of issues may be raised when the majority of transmission lines are being constructed as UG cable lines. The short cable lines in smaller network areas will have differently effects from that shown by a single long HVAC UG cable line in the network. This thesis deals with an existent 110 kV network area in the Estonian transmission network. The network modelling model is composed by basing it on data from real OHLs and UG cable lines. Issues which may become relevant to a characteristic network are modelled and analysed in reference to an actual network configuration.

This thesis analyses cable line installation options and their effectiveness in urban transmission networks. One question that is raised regards both ends being bonded and cross-bonded in terms of cable installation effectiveness. In addition, the optimum number of cross-bonding points along the cable line are also calculated. The aim of this thesis is to bring clarity into the issue of cable sheath modelling, to introduce alternative modelling approaches, and to determine their effect on network study results. Extra attention has been paid to mixed networks and concerns which may be related to transient situations in mixed lines. For a sufficient network modelling area, the transient penetration in cable lines and OHLs are also being analysed. For the purposes of research, the EMT-based software (PSCAD) has been used.

The following objectives have been set out:

- Provide a theoretical description of the differences between conventional OHL networks and cable networks
- Carry out a theoretical analysis and investigate any transient phenomena which are related to HVAC cable lines
- Investigate and identify approaches for cable sheath modelling and determine their impact on network study results
- Analyse cable sheath bonding methods and sheath bonding effectiveness, taking into consideration sheath current and voltage values
- Analyse the effective number of cross-bonding points in a cable line installation
- Determine possible concerns which may be related to mixed lines and networks
- Verify the network modelling area according to EMT studies of the cable network
- Provide guidelines for TSOs in terms of cable line planning and modelling

In this thesis the focus is on HVAC UG cables networks and cables with cross-linked polyethylene (XLPE) insulation. This thesis is not investigating DC cable lines and cable lines which are laid at sea. The emphasis is on analysing HVAC cable line installation alternatives for transmission networks and their levels of effectiveness in respect to the interests of TSOs. The better understanding will be gained in relation to underground HVAC cable line modelling for network studies, with more of a concentration on the point of view of the TSO. More precisely, the intention is to bring clarity into the realm of cable sheath layer representation in the EMT-based program cable model, providing guidelines for a proper modelling approach and its effects upon network study results.

Thesis Outline

This thesis is divided into five major chapters. The introductory chapter provides background information and covers previous research which is related to HVAC cable lines in transmission networks by pointing out the shortcomings.

Chapter 1 discusses power transmission in networks and transmission line technology. The concept of mixed networks is introduced, as are other main aspects which are related to new cable networks, such as protection, reactive power, and frequency spectrum.

Chapter 2 introduces the EMT studies and transient phenomena which are related to cable lines and cable networks.

Chapter 3 focusses on modelling cable networks in the EMT-based program. This chapter addresses the EMTP modelling principles and analyses cable sheath modelling. The results over the sheath modelling approaches are presented. Cable line installation methods are studied regarding the sheath voltage and current values and the optimum number of cross-bonding points is being analysed. In addition, a transient analysis in mixed lines is conducted to the extent of estimating the required network modelling area.

The summary with recommendations and a discussion of future topics are provided in the final part of this thesis.

1 Power Transmission

1.1 Transmission Options

Electrical power transmission using an alternating current (AC) is conventionally carried out by overhead lines. As a result of various circumstances, such as increasing population density, environmental and safety aspects, and innovation in cable technology, a growing preference has been given to cable line installations in transmission networks. OHLs and cable lines are highly different from their electrical parameters, operational characteristics, and installation aspects. Deciding which line technology to implement in transmission networks is a complicated process, with various aspects that need to be considered such as investment cost, reliability, environmental aspects, and more.

1.1.1 Overhead Lines

OHL technology has a long history, and its basics have remained the same throughout. It is a well-known system with a well-established code of practice when it comes to transmitting electrical energy along great distances.

OHLs consist of conductors (in multiples of three) that are suspended by steel towers which are set in a concrete foundation. The HV overhead conductor is usually stranded, made in aluminium alloy, and reinforced with steel strands (Fig. 1.1). Conductors are not covered with any form of insulation because the adjacent air provides the required isolation. Therefore, the OHL design requires adequate clearances between the conductive parts and between it and the ground. On the other hand, heat dissipation is easily guaranteed with bare conductors, which ensures an effective current-carrying capacity in the conductor.

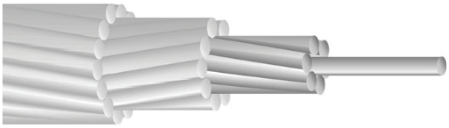


Figure 1.1 Aluminium conductor with steel reinforced ACSR overhead conductor [48].

1.1.2 Cable Lines

Cable line technology is relatively new when compared to OHL technology. In a transmission network, UG cable lines are generally used in areas in which constructing an OHL is not possible or is restricted. UG cable lines are more common at the distribution network level.

Burying high voltage conductors in the ground requires materials to be insulated for safe and reliable operation. Due to improvements that have been made in cable technology, especially in terms of insulating materials, UG cable line installations can now be used at higher voltage levels. Currently there are two main UG transmission line technologies in use, these being the pipe type, which is filled with high pressure gas or fluid to manage heat and insulate the cable, and the solid dielectric cable type. The common types of UG cable line in use are as follows [49]:

- High pressure, fluid filled pipe (HPFF)
- High pressure, gas filled pipe (HPGF)
- Self-contained fluid filled (SCFF)
- Solid cable, cross-linked polyethylene (XLPE)

Until recently (up until the last twenty-five years [13]), the SCFF cables that were mostly preferred. Nowadays, the most applicable cable type is XLPE. However, SCFF cables can still be found in the majority in a good many networks [20]. The future holds the prospect of superconducting cables [50]-[51] possibly gaining importance in the networks, as it is this type which is currently under development.

The XLPE type is the latest cable technology to come into use and has the greatest contribution in terms of cable line application. The XLPE cable has also become the standard for UG cable lines [49]. In distribution networks, XLPE cables have been made use of since the 1960s [20]. For a long time there were drawbacks in terms of improving cable insulation, so that XLPE cables could also be applicable at higher voltage levels. Success came in time, and applying XLPE cables at HV levels (up to 115 kV) started in the 1980s and at EHV levels (over 220 kV) in the 1990s [14]. XLPE cables are considered as being practically maintenance-free and make constructing UG lines much more straightforward. Only the XLPE type of cables are under consideration in this thesis.

The structure of the XLPE cable is complex, being composed of the following layers (Fig. 1.2):

- A core conductor
- An inner semi-conductive layer
- Insulation
- An outer semi-conductive layer
- A metallic sheath (screen)
- Outer cover
- Armour (optional)

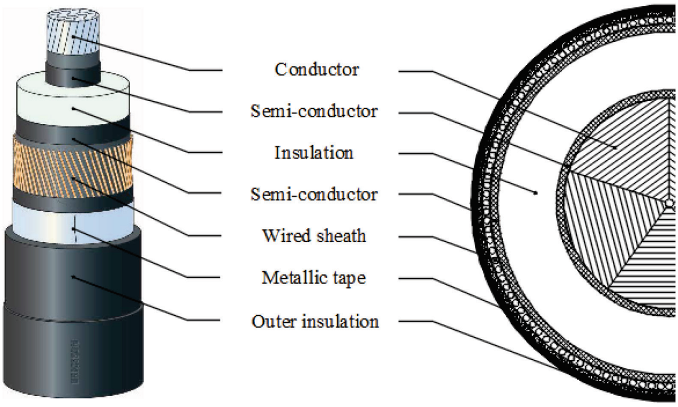


Figure 1.2 A single-core XLPE-insulated HV cable structure.

The core conductor carries the load current. It is made either of copper or aluminium wires which, in most cases, are stranded together and are segmented (also being known as a Milliken conductor). However, there can be other design types for a core conductor (such as a single strand round conductor, a hollow conductor, a stranded round conductor, a profile wire conductor, a segmental hollow conductor, and others).

For XLPE cables the insulation is cross-linked polyethylene. Insulation is one of the most important components of the cable. It protects the conductor and ensures that there is no electrical connection between the core and the metal sheath. Insulation must withstand the cable’s electrical field for steady-state and transient conditions [1].

Semi-conductive layers are used to ensure a cylindrical electrical field and to avoid any gaps which may result in partial discharges [1]. The inner semi-conductive layer is applied between the core conductor and the insulation (conductor screen) and the outer semi-conductive layer between the insulation and metallic sheath (insulation screen). The material that is used for the semi-conductive layer should be similar to the insulation material but with a larger degree of conductivity [1]. Therefore modified extrudable polymers are used.

The most complex layer in the cable structure is the metallic sheath. The metallic sheath possess several functions, such as securing the cable mechanically and providing a return path for charging currents, as well as conducting fault currents into ground [1]. Besides all this, the main purpose of the metallic sheath is to nullify the electrical field outside of the cable. There can be several types of sheaths but most often this is composed of copper (or aluminium) wires and laminated aluminium tape (foil) to ensure water tightness. The wired layer and metallic tape are welded together longitudinally with a semi-conductive tape between them.

The outer insulation (covering) is to protect the cable mechanically. For land cables this is most commonly produced with high density polyethylene. If extra protection or support is needed, an external protection layer can be added. However, this is more common for submarine cables. Land cables are not in general externally protected.

The UG cable line is commonly composed of three single-core cables. UG cable line configurations and installation are further discussed in section 1.2.

1.1.3 The Electrical Behavior of Overhead Line and Cable Line

Based on the fundamental definition of the OHL and cable line provided previously, it is obvious that there are differences at many levels between these two transmission line technologies. Besides the differences in design and installation, differences are also emerging in terms of physical properties and operational aspects. Therefore variations in electrical behaviour can be observed, and OHLs cannot be replaced by cable lines on a one-on-one in the network. The main differentiations between OHLs and UG cable lines from the network operational point of view are as follows:

- Cable lower series inductance
- Cable higher capacitance
- Reactive power
- Differences in surge impedance
- Changes in network frequency spectrum
- The presence of sheath currents and voltages in the cable line

Cable line single phase conductors are placed close to each other in the cable trench, while OHL conductor wires need to have the required spacing. Due do the smaller spacing, UG cables have lower series inductance for each unit length when compared to OHL. The inductance of the cable line is about five times smaller [23] than it is for OHL.

The presence of insulating material in the cable design, and the fact that there is only a small distance between the core conductor and the metallic sheath, results in the UG cable lines having a higher capacitance for each unit length. For example, the EHV OHL and cable line kilometric capacitances are around 13 nF/km and 234 nF/km [21] respectively. It can be said that a cable line generally behaves like a distributed capacitor in the network. According to this view, cable lines generate reactive power that brings along with it a voltage rise and a lowering of the cable line's active power-carrying capacity. In general, the cable line capacitance is around twenty times larger [23] that it is for OHL. According to [21], the kilometric reactive power generated by EHV OHL is around 0.7 Mvar/km, and by an EHV cable line it is around 11.7 Mvar/km. To ensure the required voltage level in the network and to improve cable line capacity, reactive power shunt compensation may be needed in the network. In cases in which there are more issues in the system (such as power unbalances, voltage instability, etc), Flexible AC Transmission System (FACTS) equipment can be used [50]. However, the latter is not very common and needs to be technically and economically justified. Reactive power compensation in cable lines is further discussed in section 1.5.

As a result of series inductance and shunt capacitance characteristics, the surge impedance between two transmission technologies vary considerably. Roughly said, the cable line surge impedance is ten times lower [23] than OHL impedance. As a result, the travelling wave velocity for a cable line is about half that of an OHL [23]. This becomes an important aspect in terms of transient analysis and EMT modelling.

Another concern that will arise when replacing OHL with cable lines is the change in network frequency spectrum. Cable lines are known by their effect of lowering a system’s natural frequency. As a result, there is a higher probability of resonance phenomena occurring within the network. The network frequency spectrum becomes relevant when harmonic-related issues or resonances are being studied. Further discussion on this topic is given in section 1.6.

In an area which is related to cable design, the sheath layer also plays a role in network operations. Depending upon the cable line installation, relatively high induced voltage and circulating current can be found in the cable sheath layer. This is a concern for both line operations and safety aspects. Sheath induced voltages and circulating currents are further discussed in section 1.2.

1.1.4 Choice of Line Technology

Traditionally, OHLs are preferred when reinforcing the transmission network or planning new HV lines. This is mostly due to the fact that constructing OHLs is typically considered to be more economical than constructing cable lines. Besides the investment costs, OHL preference can also be influenced by other factors, such as long term technical experience in building and managing overhead systems or the complexity of the application of underground transmission infrastructure [7]. However, after thorough analysis which considers population growth, environmental aspects, and political decisions, the cable line installation can become a more reasonable and profitable choice than OHL. Any decision over line technology should include the following aspects:

- Overall (life-time) costs
- Voltage level
- Reliability
- Safety
- Environment
- Line corridor
- Construction time and feasibility
- Electromagnetic field (EMF)

In general, the UG transmission line is considered to be between four and fourteen times as expensive as OHL [8], [49]. However, during the last decade, thanks to developments in technology and strong competition in the cable sector, costs have reduced and the performance of the cables has been improved [7]-[8]. The overall cost is hard to measure, since it comprises several components:

- Planning and design costs
- Procurement costs
- Installation and construction costs
- Material costs
- Operating costs
- Maintenance costs
- The cost involved in energy losses
- Costs which are related to the end of the operating lifetime of the equipment

It is evident that costs vary by region and are related to the construction area. They also depend upon the voltage level. At higher voltages, cable line installations tend to need greater reinforcement and ancillary facilities [49]. This may include areas such as vaults, transition structures, link boxes, and so on. Therefore it is highly important that a cost comparison be prepared for every project on an individual basis, with a determination being made of the most profitable transmission line technology.

When comparing the cost between OHL and a cable line, it has been suggested [7] that consideration be made of the overall line's lifecycle costs. The expected life of OHLs is about sixty years, while for cable lines it is forty years. There is an expected weakening in cable insulation over time. Nevertheless, due to the developments in XLPE cables [7], and with a proper installation method being used alongside monitored loading, the cable line's lifetime can be extended. The expected lifecycle of a cable line can be estimated as being comparable to that of OHLs [52], being around sixty years.

In [2], the comparative procedure for overall costs in terms of OHL and UG cables is introduced. The technical, environmental, and social aspects are included in the calculations. The comparison between the estimated costs for OHL and cable line installations can also be found in [7]-[8], [49].

When considering reliability and power availability, OHL and cable lines are both reliable in terms of their design, but are affected differently by external factors. OHLs are more greatly influenced by the weather. Lightning, strong winds, and ice storms are common reasons for OHL failures. UG cable lines can accidentally be damaged when soil and digging work is done. The vulnerability from weather conditions remains and depends upon the region. However, the risk of cable line failures occurring can be mitigated or entirely eliminated when adequate protection methods are applied (such as proper marking, reinforced ducts, and so on).

On the other hand, locating faults on an OHL is easier, with such faults being more visible, and the expected outage time being appreciably shorter. According to [49], the duration of an XLPE-type cable line outage is typically between five to nine days. For OHLs, the outage time is estimated at between one to five days. Failures which are caused as a result of extreme weather conditions may damage the OHL in a wide-ranging set of circumstances and potential sources of damage, and repair work can take months. For example, this can be seen very clearly the Great Ice Storm of 1998 in Canada (which struck Ontario, Quebec, New Brunswick, and Nova Scotia) in which thousands of transmission poles and towers, and kilometres of lines fell as part of a domino effect [53]. Overall climate change can result in an increasing number of highly severe natural phenomena, such as storms, hurricane, tornados, wildfires, and so on. According to the Climate Central report [54], weather-related power outages are on the rise. However, the failure rate in cable lines in general is very low (according to [14] which shows a failure probability of 0.03 per year).

When making a choice over transmission line technology, the line corridor also has a high level of importance. There may be specific circumstances (such as complicated natural situations which could include rivers, mountains, and so on) that cancel out one or another solution. Both OHL and a UG cable line corridor will have an impact on land use during the line's entire lifecycle. There are areas of impact that are permanent and areas of impact that are temporary. Since there can be limitations upon land use, this mostly affects the landowners and local habitants in the area. The protection zone for UG cable line is usually narrower than that of OHLs and agriculture is still allowed to take place within the vicinity. Even so, access to the cable line needs to be guaranteed if such a need arises, and the cable line corridor has to be protected from grading adjustments, digging by heavy equipment, and any kind of storage which takes place along the line corridor. In urban areas, both forms of line technology construction may involve the imposition of limitations upon traffic. The disruption is commonly greater when UG cable lines are installed, but it is an area which is highly dependent upon the method of installation being used (whether this is via an open trench or with horizontal drilling). On the other hand, OHL construction generally takes longer.

When UG cable lines are installed, any possible effect has to be considered which can be related to other communications resources which have been routed underground (such as, for example, telecommunications wires, heating and gas pipes, and so on). One primary issue in terms of public interest is, of course, scenery and any impact on the visual attractiveness of an area. Here, OHLs have a greater footprint. The visual impact is highly sensitive when it comes to local habitants and visitors. It has even been suggested [7] that the view of an area of nature which has been spoiled by the installation of OHLs may have worsening results when it comes to tourism and the local economy.

Another consideration which has to be related to HV transmission lines is the physical phenomenon which itself is related to electric and magnetic fields, known as an EMF. An EMF is created when current flows through a conductor. An EMF is a concern at higher voltage levels and is both a safety and a health issue. When it comes to UG cables, there is no electrical field due to the shielding layer, while bare OHL conductors have an electrical field that is created between the conductor and the ground. The magnetic field that is produced by UG also diminishes more rapidly with distance [7] than does that produced by OHLs.

When evaluating the options for transmission line technology, it can be concluded that there are many more aspects that need to be taken into account than simply line investment costs alone. Based on the entire lifecycle of the transmission line, a cable line will provide a viable alternative to OHLs. In the long term, a cable line tends to produce greater benefits, especially in terms of environmental, safety, and reliability aspects.

1.2 Cable Line Installation

A UG cable line, especially at HV level, is actually a cable system. A UG cable line is composed of three single-core cables that can be buried with various configurations, such as being buried in a pipe or a duct, in a trough, in a tunnel or, most commonly, directly buried in the ground or horizontally drilled. The flat or trefoil formation (Fig. 1.3) is used for the three singe-core cables (a three-phase line). Further information on UG cable line laying methods can be found in several sources in the available literature, such as in [10]. Any decision over cable line laying depends mostly upon space availability (a flat formation will require more space), and amp-bearing levels. In a three-phase cable line system, the spacing between the phases has a role in the line's operation, especially at higher voltage levels. It affects line inductance [20] and transmission capacity.

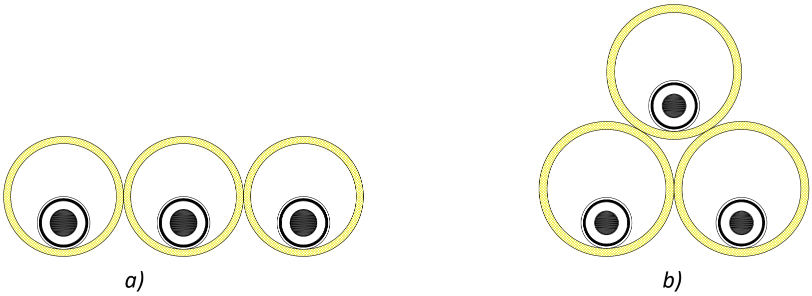


Figure 1.3 Three single-core cables in protective PE pipes a) flat formation, b) trefoil formation.

Depending on the line's length, voltage level, and its technical and configuration-related factors, a cable system can include other components and additional ancillaries besides the cables themselves. These can include joints, vaults [49], transition points, grounding system, remote controlling systems [50], reactors, and filters [50]. One of the most important components in any cable line installation is the grounding system. Any decision over cable line grounding is important because it affects the cable line in every aspect, starting from the planning process and investment costs and going all the way to the line installation, operation, and safety (both in terms of equipment and personnel). Therefore extra attention is required in this matter.

With the grounding method being used in cable line installations, any additional components become part of the cable line system. These can include the ground continuity conductor (GCC), cross-bonding points which are link boxed, sheath voltage limiters (SVLs), and so on. These components are discussed in more detail in later sections of this work. Every additional component makes the cable line system more complicated and increases line investment costs. As well as this, the need for maintenance is also increased and, with components such as cross-bonding points and SVLs, the risk of failure is higher.

1.2.1 Sheath Bonding Methods

In a UG cable line, the presence of currents and voltages in the cable sheath layer needs extra attention. Current flowing in a cable core conductor induces the voltage into the cable sheath layer. Depending upon the line length, configuration, voltage, and loading level, the sheath voltage level may become a concern at the network steady-state and may raise a risk of transient phenomena. The overvoltage in a sheath layer is a safety hazard for both line operation and equipment, as well as the personnel who are working with the line. In order to be able to suppress induced sheath voltage in a cable line, the sheath layer is connected to the ground. With a ground connection, an additional circuit between the sheath layer and ground is created. This provides a path for currents to flow in the sheath. Sheath currents result in additional losses in the cable line and reduce line capacity, as well as shortening the lifetime of the cable insulation. From the cable line operational aspects and for safety reasons, it becomes essential to control the circulating currents and to reduce the induced voltage level in any cable sheath. Therefore several cable sheath bonding methods are being developed [38]. The basic and most commonly-used methods for cable sheath bonding are as follows:

- Single point bonding
- Both ends bonding (solid bonding)
- Cross-bonding

The single point bonding system is an arrangement in which the cable sheath is connected to the ground at one end of the line. With this configuration, there is no continuous circuit between the sheath and the ground, and no current circulating in the cable sheath layer. However, there is induced voltage in the sheath layer. The proportion of sheath voltage depends upon the cable line length, its configuration, and its loading level. The sheath voltage increases with the distance from the grounding point, reaching its highest value at the other end of the cable line (not the grounded end). Single point bonding is generally an acceptable method for short cable lines, where the induced sheath voltage at the cable line's end will not reach above the allowable level (this is further discussed in section 1.2.2). In most utility companies [37] this configuration includes an additional GCC along the line for the fault current return. A surge arrester can also be used at a cable line terminal. The implementation of GCC and surge arresters depends upon the practice of TSOs and is not something that is used in several countries.

Both ends bonding means that cable line sheaths are connected to the ground in both terminals of the cable line (both the sending and the receiving end). The induced sheath voltage is therefore minimised. On the other hand, there is a continuous path for sheath currents to circulate between the sheath and the ground. This method results in large steady-state losses that can decrease the cable line's current-carrying capacity by between 10-20% [10]. Both ends bonding is considered to be the simplest sheath bonding method, one which comes with low requirements on maintenance [8]. However, with the reduced effectiveness and high losses that come with a cable line, this is only applicable for lines with a relatively low load current.

Cross-bonding is the most complex sheath bonding method. It is also most commonly used in long cable line installations. In cross-bonded cable installations, the sheaths are grounded in both line terminals, but the continuous path for sheath currents is interrupted by cross-bonding points along the line, dividing the cable line into sections. At every cross-bonding point, cable sheaths are transposed. Special equipment is used for this purpose, known as link boxes. When there are no additional groundings present in the system, besides those groundings which are in the cable line at both terminals, this bonding method can also be referred to as continuous cross-bonding. However, when needed (and dependant upon the sheath voltage level), additional sheath grounding can be added in cross-bonding points. With this system, the cable line is divided into minor and major sections. In every minor section, cable sheaths are transposed, forming a balanced system between the three phases with every third section. The additional grounding is commonly applied after every third minor section, forming a major section. With this arrangement, as presented in Fig. 1.4, both sheath-induced voltage and circulating current are affected by reducing their level (but not totally eliminating them). This system is the most effective when three-phase currents in core conductors are balanced and minor sections have an equal length. The higher number of cross-bondings there are along the line, the more effectively is the line capacity improved [10]. In real life situations the ideally balanced system is hard to achieve. With every added cross-bonding point, the line investment costs are increased. Cross-bonded installation is used in most of the longer cable line installations (those which are longer than around 2-3 km), particular with higher short-circuit [37] currents.

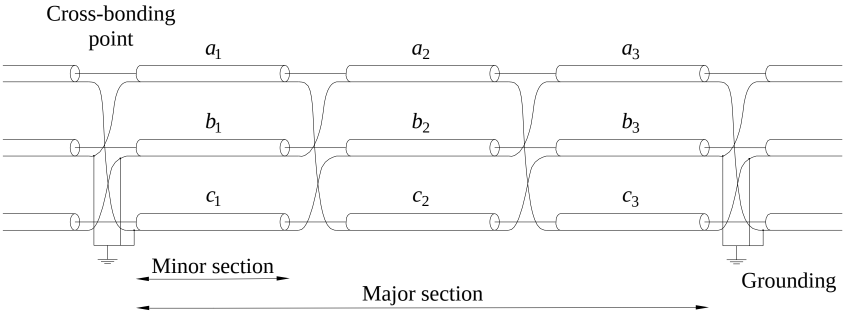


Figure 1.4 A three phase (phase a, b and c) cross-bonded cable system with groundings after major sections.

With cross-bonded cable installation, it is common practice to have additional SVLs (normally with neutral point grounded [20]) in bonding points to protect sheath cross-bonding insulators (joints) and cable insulation from flashovers and punctures [38] by limiting the overvoltage that may be caused by transients, such as lightning, switching surges, and faults. SVLs most often come in the form of Zinc-Oxide type surge arresters [37]. They can be installed either underground or on the ground in sealed boxes (link boxes), depending upon the placement of joints. SVLs can be formed in a star connection, with a grounded neutral or ungrounded in a delta connection. For technical and economic reasons, the former is mostly preferred by utility companies [37]. A more profound discussion on SVL types and their selection can be found in [38]. It may be found necessary to add the GCC into the system as well, when the grounding resistance is too high [20] and when sheath overvoltage exceeds the temporary overvoltage (TOV) rating for the SVL [17]. However, according to a survey which was conducted with the utility companies [37], it showed that for cross-bonded cable installation, the GCC is commonly not used.

1.2.2 Choice of Sheath Bonding Method

Each of the previously described cable sheath bonding methods has its own advantages and disadvantages. Any decision over the right method to use may become challenging and will depend upon various aspects:

- Cable line parameters and operational aspects (line length, voltage level, configuration, etc.)
- Sheath overvoltage level at network steady-state and during transients
- Cable line losses (sheath current level) and current carry capacity
- Investment costs
- Maintenance costs
- The complexity of the cable line installation
- Cable line protection methods
- Safety (regarding equipment and personnel)

The two most important factors when considering the bonding method to be used are the sheath voltage and sheath current levels. When only sheath voltage is considered, the most preferable option is bonding the cable sheath layer in both ends. When only sheath currents are considered, single point bonding would be the choice to make.

The cross-bonding method would be an intermediate option, when both sheath currents and voltages are under the microscope.

The cable sheath bonding and cable line grounding system has to be designed according to the voltage level that the cables and their accessories must withstand [10], taking into consideration the voltage stress at a steady-state as well as during any disturbances. Any decision has to be based on a critical analysis and by ensuring cost-effectiveness. Cable line sheath current and voltage levels are further studied in respect to the sheath bonding method in section 3.3.2.

Many utility companies rely on cable suppliers, consulting companies [37], and previous practical experience when selecting the bonding system. In some utility companies, the experienced engineers also use in-house programs and specific calculations, such as those which are presented in [37], in order to determine the expected sheath current and voltage values in a cable line. The induced sheath voltage calculations are carried out by using the EMT-based program.

In HV UG cable line planning, utility companies make the bonding decision in regards to the induced sheath voltages, where both power frequency and transient voltages are considered [37]. The rules and recommendations on allowable sheath voltage levels vary widely between countries and utility companies. Some countries have fixed rules with specific values, while others follow manufacturer references. The current practice for sheath voltage values in various countries are presented in [38]. Historically, the limit for sheath voltage fell within the range of 12-17 V, because the cable came into direct contact with the ground, with sheath damage and corrosion being more likely [38]. Nowadays, with new cable technology being available, this is no longer a problem. The most commonly utilities typically allow a sheath voltage level between 60-400 V [37]. There are examples with stricter levels, such as 25 V in Italy and more loose examples such as 600 V in Canada (in specific occasions) [38]. Under transient conditions, according to the practice of utility companies, the accepted voltage level between the cable sheath and the ground is considered as being within the range of 20-60 kV [37] (and, especially by Estonian TSOs, 6-10 kV). It is evident that there is no clear or uniform understanding about the allowable sheath voltage levels to be used in UG cable lines.

Another consideration that has been pointed out in [37] and [55] is the rise in earthing potential (known as ‘earth potential rise’, or EPR) in UG cable systems. This phenomenon is generally related to phase-to-ground faults in the network, where the fault current will flow back to the source through various paths, such as ground wires, the cable sheath, the ground itself, and any other conductor that may be present in the ground (which is often unknown). In networks there are usually ground connections in several locations, which will result in a potential rise in respect to ground-related faults [55]. The EPR, like step and touch voltage, can be dangerous for personnel. It is also harmful for system insulation and SLVs that are placed between cable sheath and the ground. The risk to SVLs depends upon their connection configuration and whether or not the GCC is included in the system. Based on various studies [37], [55], it has been concluded that EPR is not usually a concern in substation-to-substation UG cable systems where the earth impedance is relatively low (such as in urban networks). An exceptional case is the single-phase-to-ground faults [55] but these are highly unlikely when only a cable line is being considered. When the transmission line is composed partly of cable and partly of an OHL (where towers have high levels of ground impedance), the EPR needs more attention [55]. It has been found that an EPR assessment is complex and requires EMTP modelling [55]; however the accuracy of this type of study can be questionable since the data that is needed is generally unknown or barely determinable (especially in areas such as earth impedance). A detailed discussion about the EPR, and its risks and potential mitigating solutions, can be found in [55] and will be no further part in this thesis.

1.3 Mixed Networks

Mixed lines, sometimes also known as hybrid lines, are transmission lines that are composed partly with OHL and partly with a cable line. When a UG cable line is connected between two OHLs (without a switching device), the term ‘siphon’ is also used. A mixed line configuration finds application in certain situations in which installing the whole transmission line either as OHL or cable line is not a reasonable prospect or is not possible, such as in cases in which there are restrictions that are imposed by the landscape. The term ‘mixed network’ stands for a network that consists of conventional OHLs, UG cable lines, and mixed lines, and all of them at a considerable number and length. Mixed lines have not been evident until lately. In the networks of the future, especially when the transition from OHLs to UG cable lines is being considered, mixed lines will appear more often in transmission networks.

Between the OHL and UG cable line section there is a transition point. At voltage levels of up to 145 kV [10] the transition is achieved technologically by terminations on poles or towers. At higher voltages, the electrical clearances and the equipment’s physical dimensions require a special restricted area for the transition between the two line technologies. This is called a ‘transition compound’ [10], which is located close to the OHL tower.

With a mixed line configuration, there are some special aspects that need to be addressed in the network:

- Impedance variation between the OHL and UG cable line
- Differences in surge wave travelling speed
- Wave reflections and refractions in transition point
- Transients that are common to OHL can penetrate into UG cable line (the lightning transient concern)
- Unbalanced line loading levels on OHL and UG cable lines parallel work
- Higher overvoltages in the UG cable line

The impedance value in OHL and UG cable line technologies varies, being roughly ten times lower for cable lines [23]. This is due to the proximity effect and the low resistance levels of the metallic sheath [21]. The impedance in mixed lines is therefore not constant, and it changes significantly at the transition point. As a result, there is a voltage reduction being experienced when the surge wave travels from the OHL into the cable, and a voltage magnification occurs in the opposite direction [1]. In addition, reflections and refractions in the travelling wave are experienced at the transition point. The surge wave’s speed of travel in an OHL is approximately 280 m/µs, while for a cable line it is 180 m/µs. These values are considered as being valid in most cases [1]. The variation in impedance value and travelling wave propagation becomes highly important when dealing with transient phenomena.

UG cable lines themselves are subject to common faults, such as short-circuit faults, or lightning strikes in rare cases. In terms of the more frequent cases of failure in cable lines, no focus has been provided in these forms of studies. Nevertheless, in mixed lines, the OHL section is exposed to external impacts, where faults and lightning surges can be frequent phenomena. Any surge wave will travel from the OHL and penetrate into the cable line where the fault current and transient overvoltage becomes a threat to cable insulation. In practice, for short cable lines, this situation can become even more severe than may first be expected. The wave propagation can be superposed due to the reflections in surge waves that come from the line receiving end.

The most severe conditions normally involve lightning surges [37]. In [44], a long cable line with a siphon configuration is analysed in order that the appearance of maximum lightning overvoltages may be investigated. Worst-case scenarios are considered as being shielding failures and back-flashovers that occur close to the termination point, where the highest overvoltage propagates into the cable line. The overvoltage level in the cable line is hard to predict. There are multiple reflections between the grounded towers where any lightning current is diverted into the ground and is dispersed between the conducting surfaces (which may otherwise be unknown, such as pipes and so on), which strongly decreases the current value. In the planning stage, the potential stress which originates from OHLs and related mitigation methods need to be considered. It is recommended that each case be analysed individually [44], since making any generalisations and assumptions may result in uncertainties.

In meshed networks and at substation entrances, OHL and UG cable lines can often run in parallel. In these cases, extra attention on line loading levels is required. Since the impedance of a UG cable line is lower than that of an OHL, the higher loading current will be carried by cable. This situation will produce an unbalance and will result in the inefficient use of any installed transmission capacity. An overloading cable line may also become a risk. As a mitigation method, a cable system with a larger transmission capacity can be considered or the installation of series reactance in the cable line section may be used to increase impedance value (or series capacitors on the OHL section instead). This situation requires attention and analysis at the network design stage. To be able to control the current flow and correctly dimension the cable line, the network configuration and loading levels have to be considered.

To protect the cable and to limit overvoltage penetration into the cable line itself, voltage limiters are used at line transition points. However, due to the reflections and refractions in the cable line, a higher overvoltage can still occur inside the cable line. The correct dimensioning of any voltage limiter can be a challenging process, but this is of a high level of importance from the equipment and line protection point of view.

Analysis and discussions that are related to mixed lines are further discussed in section 3.

1.4 Protection

Since UG cable lines and OHLs have different physical and electrical characteristics, the transmission line protection aspects need to be re-evaluated when considering the replacement of OHLs with UG cable lines. The existing protection policies and schemes may require changes [50]. The most substantial change could be the operation of the distance relay (or impedance relay) [50], because cable lines have lower impedance levels when compared to OHLs. With mixed lines in the system, the mitigation and reduction of any overvoltage which may originate from OHLs becomes a very relevant prospect, as does a reconsideration of the use and operation of an auto re-closer, which is something that is normally applied on OHLs.

OHLs are mostly provided with an auto re-closure because faults on OHLs can often be temporary and self-recovering. Cable line faults, on the contrary, are permanent and are not self-recovering; therefore an auto re-closure is not used. An auto re-closure in mixed lines is something that needs careful examination, since it can lead to overvoltages in the transition point between the OHL and the cable line itself [50]. From the technical point of view, re-closing mixed lines is possible and, in some circumstances, an auto re-closure can be acceptable. The principles behind when an auto re-closure can be applicable in mixed lines are introduced in [23], with examples including during storms, when low fault currents occur, and so on. However, there are some risks related to cable lines that need to be evaluated, such as additional voltage dips and possible cable damage [50].

One option would be not to use auto re-closure at all. This is an option when the OHL part of any mixed line is relatively short and other measures have not been taken (such as offering a protection level against lightning, providing redundancy in the grid, or incorporating safety aspects) [50]. In general, removing any auto re-closure option massively increases the line's risk level and is not advisable.

The more developed principle is the lock-out system for faults in the cable line itself. This means that if there is a fault in the cable line, the auto re-closure will not operate [50]. This system needs additional current transformers, and measurement and telecommunications channels to be able to detect any faults and, therefore, it is a rather complicated system.

In an HV transmission network, any distance protection is used where it is based on the linear increase of the impedance over the line length [50]. Cable lines have lower impedance levels than do OHLs, as well as deviations which can appear in the linear impedance curve, because fault return paths can vary depending upon the type of fault being experienced (whether core-to-sheath or core-to-sheath-to-ground), while the fault location and sheath bonding method are also different [50]. Finding the right setting for a distance relay can become a challenging process, and it needs a more detailed analysis. For longer cable lines, accuracy can be achieved more easily than it can for short cables. Thanks to modern digital distance relays that are capable of distinguishing between multiple sections, distance protection is becoming an applicable protection system even for mixed lines. Distance protection in cable lines can be considered as being a backup, and more reliable differential forms of protection (which are normally used for full cable connections [50]) are being used as a first option in terms of telecommunications needs.

A lightning-related event in relation to the OHL results in significant overvoltages in the cable sheath layer (section 3.5). To be able to control overvoltages which originate in the OHL (such as lightning and switching overvoltages), and to protect the cable line, its sheath layer, joints, and cross-bondings, and the surge arresters and SVLs are all used. Surge arresters are commonly connected to the termination point between the OHL and the cable line. However, it is suggested in [10] that surge arresters be used at both ends of the cable line whenever possible (except with cable lengths that are below 50 m). SVLs are used in cable line cross-bonding points. The correct optimisation of surge arresters is important on both sides, whether it is the arrester's ability to withstand any surges or line protection in general. Surge arresters must be designed to provide protection against transient overvoltages which are compatible with the equipment's ability to withstand such overvoltages. On the other hand, surge arresters must resist the highest possible overvoltages at the power frequency under fault conditions [23]. Optimising and choosing the correct surge arrester is discussed in more detail in [23] and [10].

1.5 Reactive Power Compensations

In HVAC networks that contain (long) cable lines, installing reactors into the network may become necessary. Cable lines have higher levels of capacitance, being about ten or twenty times [1] higher when compared to OHLs. High capacitive components result in higher reactive power generation, in respect to Eq. 1.1 [50]. The reactive power that is generated by a cable (Q_{cable}) is also proportional to the square of the line voltage (V). Since cable capacitance (C) is proportional to the line length, the generated reactive power increases with the cable length and, therefore, reactive power becomes more of an issue for long line lengths.

$$Q_{cable} = 2\pi f C V^2 \tag{1.1}$$

Higher reactive power generation into the network results in two additional concerns. Firstly, the voltage level in the cable line and at the nearby network nodes rises. This is caused by the *Ferranti Effect*, a phenomenon that appears when an unloaded or lightly loaded line is energised and the capacitive current in the line is higher than its loading level [1]. The second concern with reactive power generation in the cable line is that it reduces cable line capacity when it comes to carrying active power. In order to be able to avoid any voltage rise and ensure a line’s active power capacity, the surplus reactive power needs to be consumed. Shunt reactors are installed along the HVAC cable lines or at line terminals to compensate for the reactive power.

The shunt reactor installation needs throughout consideration and analysis in the network. The number of reactors, their location, and the correct dimensioning of operational characteristics is essential. There are a large number of transients that can be directly related to interaction between the cable line and reactor and the rest of the network, with such transients involving leading current interruption, the zero-missing phenomenon, cable discharge, and so on. The reactor is an inductor (one which is comparable to the transformer in the network), and interaction with a capacitive cable line most commonly results in harmonic distortions and overvoltages due to the resonances. To be able to optimise the cable system and determine whether reactors are needed, how many there should be, and what the compensation rate should be, the system need to be analysed in regard to various aspects of it. Both no load and full load network conditions need to be considered. Reactive power compensation in UG cable lines is discussed in more detail in [1], [23], [56].

Since reactive power compensation becomes more relevant for long cable lines (especially those which are longer than 20 km [23]), it is assumed that in urban networks with relatively short cable lines, reactors are not needed. It is stated in [23] that for areas with a high concentration of short cables or with lower voltage levels, it may be appropriate to carry out area-wide studies in order to determine the reactive power compensation needed and to be able to optimise the system.

It is not the task of this thesis to investigate reactive power compensation in the cable lines or networks. However, introducing the possible transient phenomena which are related to the interaction between shunt-compensated UG cable lines and the network has been seen as a subject that it is important to introduce, and this is further discussed in Chapter 2.

1.6 Frequency Spectrum

By their nature power system components can be classified as inductances and capacitances. It is already well known that inductances and capacitances interact with each other, causing resonance points in the network. At these certain points with a certain frequency being used, series and parallel resonances may appear. Resonances bring along with them harmonic distortions and TOV in the network. These effects need to be studied individually in order to be able to understand what type of transient phenomena may occur in any respective network. A frequency scan will determine the network frequency spectrum and will help in any evaluation of possible resonant frequency points in the network. An overview of how to estimate the frequency spectrum is presented in [1].

The frequency spectrum at a certain point in the network is different when an OHL-based network and a UG cable line-based network are being considered [1]. Cables have larger capacitance levels (in terms of capacitive charging current) and, therefore, the resonance frequency is lower, which means that it is closer to the power frequency when compared to an OHL network. The frequency spectrum at a certain point in the network depends upon the length of the cable being energised, the length of the neighbouring cables, and the waveform reflection/refraction coefficient [1]. When the share of cable lines in a network increases or full cable networks are considered, the resonance points tend to appear at lower frequencies. This means that there is a higher possibility of resonance phenomena occurring in the network. In addition, the magnitude of the resonance impedance in cable networks also tends to be lower [1], [6]. Another aspect is that system resistance level have a dampening influence upon the resonances. Since cable networks contain lower resistive components, the damping of these oscillations is also lower [1]. Variable network loading levels should be taken into account when assessing the network frequency spectrum.

Cable line cross-bonding will have an effect upon network resonance frequencies as well. According to the study results in [6], a cross-bonding cable sheath will increase the number of resonance points in networks. In addition, the resonance impedance is higher at parallel resonance points and lower at series resonance points when compared with the cable being bonded in both ends. Examples of the changes in network frequency spectrum, covering instances in which an OHL-based network and a UG cable line-based network is being considered, can be found in [6] and [23].

It can be concluded that by increasing the share of cable lines, the harmonic distortion level in the network also increases. Lower harmonic resonances may result in TOVs. These overvoltages have a sustained nature and result in additional currents [50], which may cause overheating and can damage the equipment. For example, surge arresters which have been applied in a network are not meant to operate in TOV situations and their capability to withstand energy absorption can be exceeded. It is clear that resonance and overvoltage studies have gained higher levels of importance and need more attention when cable lines are being planned in any transmission system.

2 Electromagnetic Transient Phenomena and Studies

A transient phenomenon is the consequence of an event that takes place within the power system, when there is a rapid change in the network. For example, such changes in a network may be caused by lightning, switching events, or just through network transitions from one steady-state condition to another. With these events, the network's normal balance is disrupted and abnormally high voltages (overvoltages) can occur. These overvoltages can be harmful for network equipment and operations.

A transient phenomenon is a short term event, one which usually takes place in a period of milliseconds or less, but the peak values which occur in the network current and voltage may be dangerously high. The main types of overvoltages are as follows:

- Temporary overvoltage (TOV)
- Slow-front overvoltage (SFO)
- Fast-front overvoltage (FFO)
- Very-fast-front overvoltage (VFFO)

In the cable lines and cable networks, the focus is more on the TOVs and SFOs. FFOs are usually lightning-related events and VFFOs are related to networks which have gas insulated (GIS) equipment. In networks which have mixed lines, lightning-related events need to be considered in a concept in which OHL lightning overvoltages penetrate into nearby cable lines.

In the network planning and system operational point of view, EMT studies become highly relevant for TSOs when it comes to estimating transient events and overvoltages in a network, optimising equipment and insulation levels, and in terms of network operation, as well as with protection. For EMT studies an EMT-type tool (EMT-programs (EMTP)) is used. This type of program is developed for the study of a power system with a high level of precision [57], and to reproduce the actual time-domain waveforms. The history behind transient analysis and EMTPs can be followed in [17] and the basics of EMT theory are covered in [58].

In this chapter, the usual EMT studies are discussed and transient phenomena are introduced where they are related to UG cable lines.

2.1 Electromagnetic Transient Studies

There can be several reasons for EMT studies being conducted within a network, depending upon the purpose of the outcome. These can include, for example, planning purposes, in order to be able to dimension the lines and equipment, or for stability, reliability, or power quality reasons. Any studies and analysis that may be needed are regulated by the network operator.

OHL networks have a long history. Their operational aspects are commonly known and they have been very well used over the years. UG cable lines with their complex structure are rather newer technology, with the relevant knowledge and know-how being under constant development. There are several specific transient phenomena that can arise in relation to long cable lines when reactive power compensation is included (such as the zero-missing phenomenon). These types of phenomena emerge only in particular circumstances and network configurations, and are dependant upon the voltage level, line length, and the purpose of the cable line in a power system. For the purposes of these studies, exact information about existing (or planned) equipment and cable line installations is required. It is more or less these types of EMT studies that become more relevant in profound and more specific network planning stages, where any decision over line installation has already been made.

Transient phenomena in individual long cable lines (with reactive power compensation) have been studied in previous works, such as [17], [23], [59]-[60]. There is no well-known understanding of any of the concerns that are related to meshed networks with relatively short cable lines. Any cable network analysis is complex, and various aspects across a wide range need to be considered. The individual approach is required for every system when it comes to its configuration and characteristics.

In the cable system planning process, studies which are related to line transmission capacity and the reactive power compensation ratio are amongst the most-frequently conducted. The results will provide the information that is needed for the cable route, the voltage level (which for the most part has already been determined by the system), the conductor size, and the necessity for shunt reactors [17]. The transmission capacity study and reactive power study will affect other studies that may be required for laying a cable system. Fig. 2.1 shows how cable system studies are very strongly related to reactive power compensation.

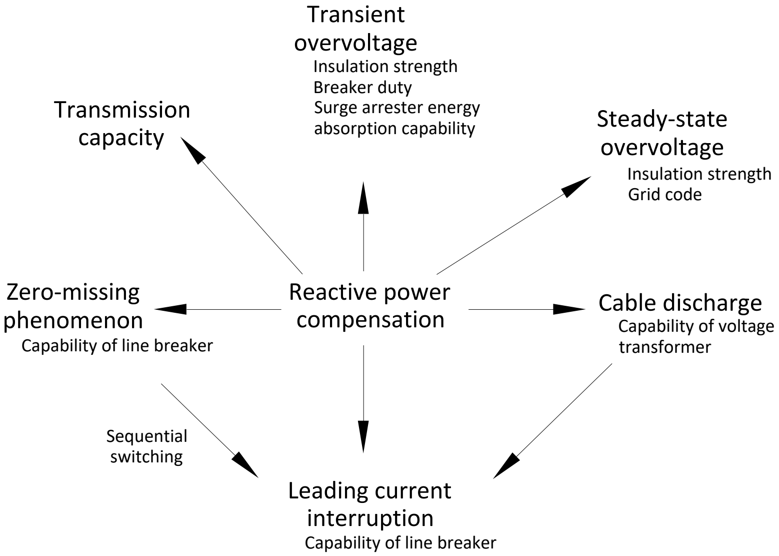


Figure 2.1 Transient phenomena and studies in cable system that are related to reactive power compensation [17].

According to the survey that was conducted amongst utility companies and manufacturers, as presented in [37], cable lines are most often studied for their power frequency (steady-state) and transients. Switching and lightning transients are considered in the network design process, especially in terms of sheath protection. Lightning events (in mixed lines) are believed [44] to be the most severe of events, more specifically in terms of their effect on shielding failures or back-flashovers close to the cable entrance. In conventional networks a lightning surge has a dampening nature due to higher levels of impedance, while in cable networks (especially with short cable lines) the damping effect is lower and TOVs may last for a longer period of time with higher magnitude surges.

The cable line bonding method will also have an effect upon the nature of a network study. It is stated in [37] that, for power frequency faults in cross-bonded cable installations, the most severe events are three-phase or phase-to-phase faults. The studies that have been conducted as part of this thesis have considered the most common cable line installations, both ends bonded and cross-bonded cable installations.

For short cable lines, various fault situations are more relevant than the specific transient phenomena. Faults are also one of the primary disturbances in a network when it comes to analysing the network strength, dimensioning the line, and decide on its installation method. Therefore, in the network planning process, the fault situation gains primary importance. In this thesis, the focus is on network steady-state operations, fault events (on line terminals, the network bus, the nearby OHL, and so on), and lightning-related events (the network bus, or the mixed line OHL section).

These types of studies are helpful for the network operator, helping them to determine the opportunities for and limitations on cable line installation, and ensuring operational safety for the sheath layer and the entire cable system.

2.2 Faults

Significant numbers of transients in the power network are directly or indirectly associated with faults [1]. Fault situations, like phase-to-ground or phase-to-phase short-circuits in OHL networks, are common disturbances. In cable line systems, these fault occasions are rather rare because cable lines are not prone to the direct external impact. Nevertheless, fault situations in any cable system need to be analysed, since a faulty current return path is a complex issue in cable lines. There are various paths for a fault current to flow through and, due to the presence of mutual coupling, all phases are influenced by the fault. The returning fault current is divided between the ground return and cable sheaths, including the sheaths of un-faulted phases, since sheath layers are connected in the cable line terminals. The fault current flow in the cable sheath is strongly dependent upon ground resistance (being able to determine the exact value is challenging) and on the line installation method, whether groundings and cross-bondings are implemented in the sheath layer or not.

A fault current in a faulted phase conductor will induce the voltage into healthy phases thanks to the mutual coupling between conductors. Cable lines in a three phase system are mostly laid close to each other, with the result that the voltage that is generated into the sheaths will be within the same range for all three cables in the system, with a slightly higher value for the faulted phase. Since the induced voltage level depends upon the arrangement between the cables, the cable system’s laying formation, whether a trefoil or flat formation has been implemented, will also have an effect.

Faults have various causes and different characteristics. In the cable line system, the faults can always be considered with including the ground connection. Internal faults on a cable system (originating from the cables and not being related to any external impact) are rare, and cable insulation breakdowns are usually caused by a fault in some other part of the network. More probable in terms of occurrence are fault events outside the cable system and fault current and overvoltage penetration into the cable system, such as faults in the cable line terminals (at the substation), faults, and lightning surges on OHLs that are directly connected or which are near to the cable line.

With fault currents flowing into the cable system, and with the returning path running through the cable sheath layer and inducing voltage into the sheath layer, there is an extra stress which is revealing of cable insulations and the sheath layer. To dimension a cable system and ensure its reliable operation in fault events, the current and voltage values in the cable sheath layer need to be studied in the cable system planning process.

This thesis focuses on the level of sheath currents and voltage in fault events, in order to determine possible issues in and limitations for cable line installations. Three phase-to-ground fault and OHL lightning-related situations were considered, and an analysis was conducted on the general effect upon mixed network operation (the impact on network bus voltage values) and fault current penetration in a transmission network, with the results being presented in [I]. The cable sheath current and voltage levels in a single phase-to-ground fault at the cable line receiving end and during a lightning-related event on the OHL part of a mixed line have been published in [II].

2.3 Cable Energising and De-Energising

Overvoltages which originate from line energising are for the most part reported as SFOs. What has not been reported is that SFOs in cable system exceed the insulation strength level [20]. Since the SFOs are generally not an issue in conventional OHL networks, they are often understudied in cable networks as well.

Line energising and de-energising by their nature are line-switching events. Cable line energising can be considered as being a simple inductive and capacitive component (LC) parallel circuit that is connected to the network voltage source. When a cable line is being energised, the capacitive component charges through the inductance, resulting in oscillations between capacitance and inductance. The oscillation between the components is different from the network frequency; therefore the capacitive component voltage and the network voltage reach peak values at different moments in time. The amplitude of the line energising overvoltage waveform depends upon the line-switching moment and the voltage value on the circuit breaker. When energising takes place at a point in time in which network voltage at the circuit breaker terminals is at zero, there is no difference between the network voltage and the capacitive component voltage value, and the switching overvoltage is at minimum or does not exist at all. On the contrary, when network voltage is at its maximum value, there is a difference in voltages and the resulting energising overvoltage is at its peak value.

Another matter is that of cable line de-energising. When cable lines are de-energised, the energy is being stored in the capacitive component. It will take some time for the remaining energy to scatter into the network. According to [1], this may take several seconds, depending upon the capacitive component (line length). This phenomenon is similar to that of a discharge of a capacitor. Since, within the cable line, the storage voltage value is considerably lower and the resistance is higher when compared to a conventional capacitor, it has been stated in [1] that cable line de-energising will not result in major issues in networks. Extra attention to this phenomenon is required when cable lines are being re-energised. The time required before a cable line can be re-energised should be enough for the residual energy to scatter into the network. Cable line discharge is further discussed in section 2.4.

Transient overvoltages which originate from line-switching events are highly dependent upon network configuration, line parameters, interactions between the equipment and, of course, by the switching point in terms of time. Therefore studies covering switching events need multiple simulation runs so that the afore mentioned aspects can properly be considered. For example, switching studies which have been analysed in the long EHV cable line in Denmark can be found in [59].

2.4 Cable Discharge

Cable line discharge becomes more relevant when shunt reactors are connected to the line. When the cable line is being de-energised and disconnected from the rest of the network, the line discharges through the reactor. In this case, the quality factor *Q* of the reactor determines the time at which the discharge process takes place. It is stated in [17] and [20] that for EHV shunt reactors the discharge process may take around eight minutes.

When the cable line is re-energised too soon and there is some remaining energy still being stored in the cable line which is the opposite to the network voltage [17], this will result in a voltage impulse at the point at which the cable line is re-energised. If this voltage impulse exceeds the voltage level that the switching impulse can withstand (known as the 'switching impulse withstand voltage', or SIWV), it becomes dangerous to the equipment and to the system. Residual energy dissipation needs to be considered when the auto-reclose is applied to the line. For example, according to [17] at least ten minutes should be allowed to pass before the cable line is re-energised.

If a shunt reactor is not used in the cable line, the line discharges through the voltage transformer (VT) [17]. The inductive VTs need to have enough of a discharge capability for sequential switching also to be able to dissipate the heat after dissipating the cable charge [17], which may extend the entire process by as much as several hours.

2.5 Leading Current Interruption

Since HV cable lines have a high capacitive component, there is a capacitive current that needs to be switched by the circuit breaker. Capacitive current switching requires additional attention by considering the switching time moment. The circuit current is interrupted at its zero value, but voltage at this moment is at its peak value, due to the 90^0 shift between current and voltage waveforms. This means that a re-strike can occur and there may be higher overvoltage impulses. This phenomenon is called leading (capacitive) current interruption. Re-strikes can be repeated and overvoltage impulses can reach severely high values, resulting in potential equipment and insulation damage. The equipment's leading current interruption capability has to respond to the withstand level.

The leading current is more of a concern in long EHV cable lines (400 kV over 26 km [20]), where the capacitive current is higher and where the cable lines are not compensated by a shunt reactor. When the cable line charging current is compensated by a directly-connected shunt reactor, the leading current interruption capability is not a concern.

2.6 Zero-Missing Phenomenon

The zero-missing phenomenon is a concern with long cable lines that are compensated by directly-connected shunt reactors and where the compensation rate is at more than 50%. The zero-missing effect can happen in the first few seconds [50] after cable line and shunt reactor switching, and it is a high risk problem for circuit breakers. Because of the temporary aperiodic current component of a shunt reactor, the current will not have a zero crossing for a few hundreds of a millisecond [50], which means that circuit breaker cannot be opened without re-ignition and damage to the breaker (except when the breaker is designed to interrupt DC currents or is open at the non-zero current [1]).

The decay of DC current depends upon the cable and reactor resistance and its initial value on the voltage at the reactor terminals and reactive power compensation level. The zero-missing phenomenon poses a severe risk to network equipment. There can be several countermeasures put in place to be able to mitigate the issue, such as varying it with reactive power compensation levels, using pre-insertion resistors, single phase dripping, and so on. The zero-missing phenomenon is related to specific long cable line installations where the reactive power compensation rate is above 50%. A more detail discussion about this phenomenon can be found in [1], [17], [20].

2.7 Resonances

Resonance phenomena are the result of interaction between capacitive and inductive components in a network. Most frequently, the resonance phenomenon is discussed as a form of interaction between cables and transformers, where the cable represents the capacitive component and the transformer inductive component. When the cable line is connected directly to the transformer extra attention is needed. Resonances lead to steady-state harmonics issues, as well as being able to cause an overvoltage, and may lead to equipment overheating.

When transformer inductance creates a series connection with cable capacitance, a series resonance can occur during cable energising, resulting in a high TOV in the cable and at the transformer connection point. When the energising current contains a frequency component which corresponds with the resonance frequency of the grid and cable (LC) combination, an amplification occurs in the resonance [50]. In an actual network it is unlikely that the cable line and transformer are energised together. However, in meshed networks several lines (and series transformers and cable lines) are connected to the same bus. With any transmission line energising, and with the presence of transformer and cable line series connections in the network, the energising overvoltage can travel into the series circuit. In networks with (long) cable lines, the energising dominant frequency can be relatively low and a resonance phenomenon can appear more easily. Since the overvoltage damping is also weaker, the resonance overvoltage can appear in network locations that are farther afield.

Another resonance situation is that of parallel resonance, which occurs during the transformer energising process, where a shunt reactor with its inductive component is connected to the cable line, creating a parallel resonance circuit. If the parallel resonance circuit is connected to the current source and a transformer which is quite some distance from the source is energised through the cable line, there will exist a high level of impedance between the current source and the transformer [6]. This means that any current flows into the parallel resonance circuit and, in the case of there being a match in natural resonance frequency, an infinitely large voltage can appear. Besides the transformer and cable line energising, the HVDC can also be a source of harmonic current which excites the resonance circuit [59]. However, the most severe form of risk is considered to be the transformer energising through the cable line (with a shunt reactor), because the inrush current has high harmonic content, a low frequency, a low damping, and long duration [59].

There can also exist a ferroresonance issue between the transformer and cable, which can occur when transformer and cable are being isolated and the circuit breaker one phase opens while the other two remain closed [23]. In this situation, the capacitive component is in series with the transformer magnetising characteristic, and sustained

TOVs can appear. This situation is more common in medium and low-voltage grids (distribution networks), due to the use of fuses.

In cable networks, resonance phenomena become highly essential. In order to be able to detect a possible resonance phenomena situation in a network, a frequency scan is required to determine the resonance frequency points. On the other hand, this is directly related to the precise network configuration, meaning that each network needs to be studied on an individual basis in respect to its configuration and characteristics. Therefore it is not the job of this thesis to further analyse the occurrence of resonance phenomena in cable networks. Resonance phenomena are discussed and explained in more detail in relation to the specific network configuration in [59], with an overview regarding how the natural and dominant frequencies may be detected.

3 Cable Network Modelling

In Chapter 1, the differences and specific aspects that are related to cable lines (networks) were discussed. It became clear that the electrical behaviour of UG cable lines is significantly different to that of OHLs. In Chapter 2, EMT studies were discussed in terms of cable networks and transient phenomena that are particular to cable networks. From the network planning point of view, these aspects need to be considered and analysed. Therefore cable line (network) modelling in EMT needs closer consideration. The simulation results can only be as accurate as the input data and simulation model. This chapter focuses on the modelling work that is carried out for cable networks and studies that have been conducted which are related to the objectives of this thesis, and points out the main results.

The EMTP/PSCAD simulation model composed below is based on an actual grid, being part of the Estonian 110 kV transmission system (in urban areas), as shown in Fig. 3.1. Network modelling area includes eighteen network buses (substations) and the rest of the network being modelled as system equivalents (*EQ*) at the borders. The network is characterised by OHL and UG cable lines at the proportions of 70% and 30% respectively. Transmission lines are rather short, with a maximum line length of up to 8 km.

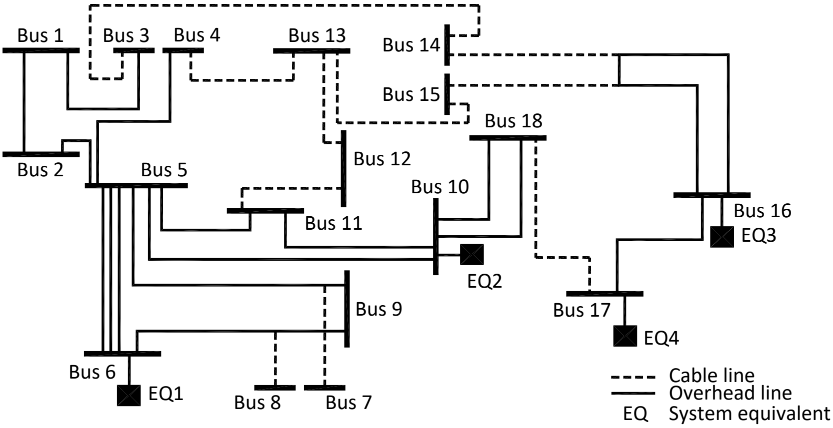


Figure 3.1 The 110 kV transmission network area (involving mixed lines) under study [I].

The full modelling network (Fig. 3.1) is employed for those studies which consider a greater or more general influence area. These involve the cable sheath layer modelling effect upon simulation results and the extent of the network modelling area for transient studies. These study results are presented in [I] and are discussed in section 3.3.1 and section 3.6.

The larger is the network modelling area the more time consuming becomes the simulation. For those studies and effects that are related to cable line installation, interest is more concentrated on a particular point in the network, such as a certain network area or line. Therefore it becomes somewhat more effective to be able to reduce the network modelling area. For the cable line sheath current and voltage level studies that have been presented in [II] and in section 3.3.2, the network modelling area (Fig. 3.1) was reduced so that the network area which consisted mainly of OHLs was excluded (Bus 1, Bus 2, and Bus 5 to Bus 10), as shown in Fig. 3.2. The particular cable line under focus here is part of a mixed line between Bus 15 and Bus 16. The proportion of OHLs and UG cable lines is 3.2 km and 3.7 km respectively. The analysis of the number of cross-bonding points in the cable line installation ([II] and section 3.4) and the mixed line studies (section 3.5) are conducted by basing them on the same network area and cable line model.

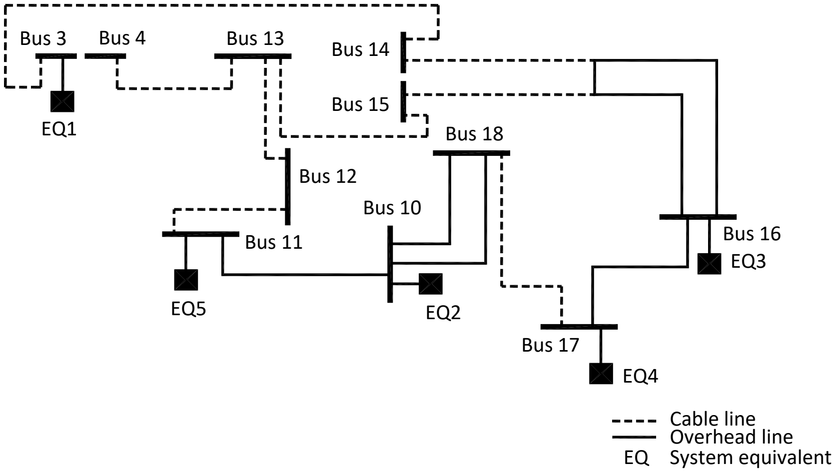


Figure 3.2 Reduced 110 kV transmission network area for analysing cable line sheath current and voltage levels.

To be able to compare various cable sheath modelling approaches at the frequency domain and to analyse their impedance characteristics response, an even more simplified simulation model treatment is being used, with only a simple single cable line representation without any surrounding network. Accordingly, the cable sheath impedance characteristics in the frequency domain are analysed and the study results are presented in [III].

3.1 Existing Models for Transmission Lines

The relatively straightforward *Kirchoff's* circuit laws can be used for fundamental transmission line modelling. However, this means that results respond to a specific frequency in a network steady-state condition. In the cable lines, no current flow in the sheath layer is included with this basic method. This cannot be considered as an accurate method of calculation for network studies. Transmission lines are nonlinear in nature and, due to the skin effect, the impedance is frequency dependent. Besides this, with cable lines there is an additional circuit for a ground return. These aspects are essential in EMT simulations and also in order to be able to obtain accurate study results.

To be able to represent frequency-dependent transmission lines in a time domain EMT simulation, the frequency-dependent parameters need to be converted into their equivalent time domain characteristics [61]. This can be done by implementing various modelling techniques.

For cable line models, the common modelling models can be divided into lumped parameter models (Pi-models), and distributed (travelling wave) parameter models (Bergeron and FD-models). The latter method is most preferred for modern network studies.

The Pi-model is the classical line modelling method, and the simplest, one in which the cable line's total inductance, resistance, and conductance is modelled as lumped parameters. To use the Pi-model other than in terms of the fundamental frequency, many short Pi-sections need to be used to distribute the line parameters (the 'Exact Pi-model'). Pi-models are applicable for short cable lines, where travelling wave models cannot be used due to the time step constraints [61]. When the cable length increases, errors in the results become noticeable. Pi-models are not considered as being efficient for transmission line transient modelling in EMT.

The Bergeron model is the oldest and least accurate [61] from the point of view of distributed parameter models. This represents the system L and C components in a distributed manner. The Bergeron model can be compared to an infinite number of series-connected Pi-sections, in which the total system resistance R is lumped (with half in the middle of the line and a quarter at each end) [6]. This means that the Bergeron model represents system parameters accurately at a constant frequency, just as does the Pi-model, but areas other than the fundamental frequency can be calculated (such as higher frequencies). The implementation of the Bergeron model in EMT studies can be justified when computational speed is more important than accuracy, and when frequency-dependent input data is missing.

Frequency-dependent (FD) models are the most accurate modelling models to represent line full frequency dependency parameters and the total system resistance R as a distributed parameter. The propagation and admittance matrices are used. In FD models the calculations are made in the frequency domain and are converted into the time domain by means of Fourier-transform or Z-transform.

There are two FD models available: the FD mode model and the FD phase model. The latter is the newest and most highly recommended [61] for studies that involve transmission lines (including UG cable lines). The difference relies [61] on the functional approximation of various parameters. For the FD mode model these are attenuation function and characteristic impedance, and for the FD phase model, they are characteristic admittance and the propagation function. The FD phase model is more accurate and stable than the FD mode model and should always be favoured in EMT cable line studies.

Table 3.1 Modelling models suggested for various phenomena simulations in cable networks.

Transient Phenomenon	Model
Switching overvoltage	FD-model
Zero-missing	Bergeron or lumped
De-energising	Bergeron or lumped
Series resonance	FD-model
Parallel resonance	FD-model
Ferroresonance	FD-model
Faults	Bergeron
Frequency scan and Harmonic sources	FD-model

Table 3.1 provides a short overview of suggested modelling models for various phenomena related to cable networks. Several earlier areas of research can be found, such as [1], [5], [25], and [62], which compare the existing models of transmission line modelling and determine a suitable model for EMT cable system studies. It has been

found that the most accurate and appropriate model for cable line modelling is the most highly-developed FD phase model. However, for specific studies the highest level of accuracy may be less irrelevant and the same results can be accomplished by using a simpler modelling model with a faster speed of computation. In [1] and [23], the overview is presented of cable models which have been suggested for various types of simulations. A short overview has been highlighted in Table 3.1.

3.2 Cable Modelling Principles in PSCAD

In this thesis, the PSCAD modelling software is used. PSCAD (Power Systems Computer Aided Design) [63] is a flexible graphical user interface for the EMTDC (Electromagnetic Transients including DC) simulation engine which enables users to schematically construct a circuit, run a simulation, analyse the results, and manage the data in a completely integrated, graphical environment [64]. To construct a UG cable system in PSCAD, two pre-programmed components are needed, as illustrated in Fig. 3.3. These are the cable configuration (Fig. 3.3, centre), and cable interface components (Fig. 3.3, left and right). These components work together and cannot be used separately. The two Cable Interface components represent the cable system sending and receiving ends. The purpose of these components is to connect the cable system to the rest of the electrical network [64].

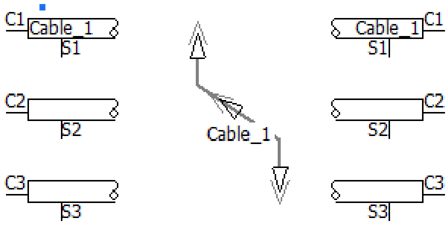
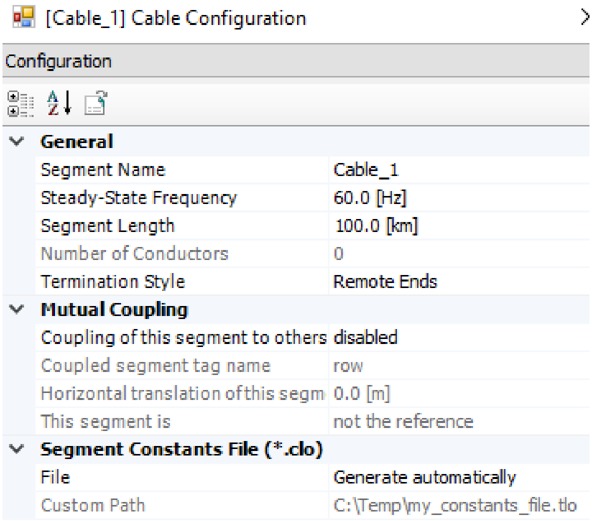


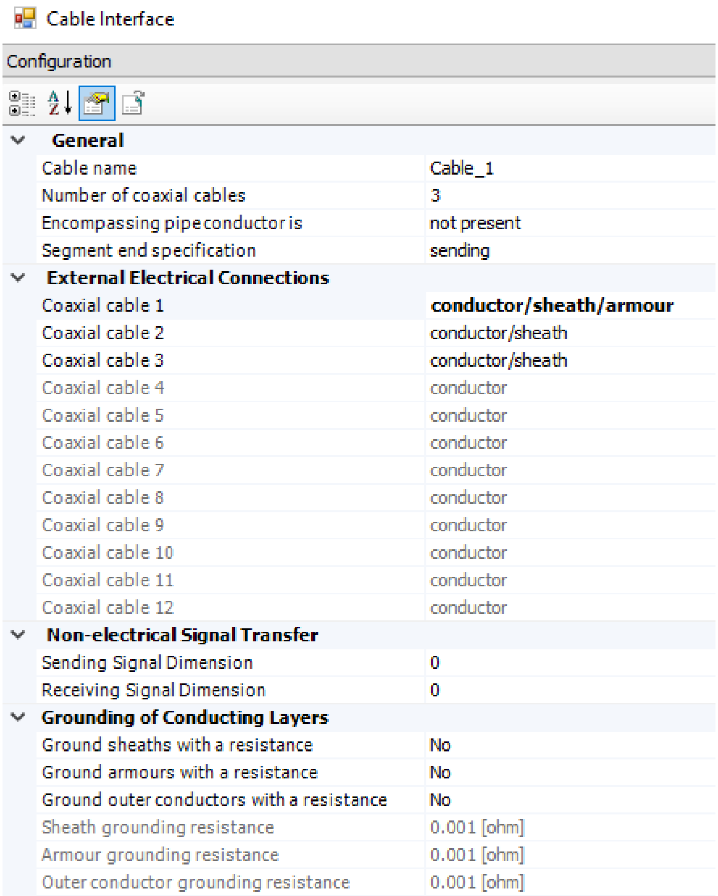
Figure 3.3 Cable system constructed with Cable Interface (left and right) and Cable Configuration (centre) components in PSCAD software [65].



General	
Segment Name	Cable_1
Steady-State Frequency	60.0 [Hz]
Segment Length	100.0 [km]
Number of Conductors	0
Termination Style	Remote Ends
Mutual Coupling	
Coupling of this segment to others	disabled
Coupled segment tag name	row
Horizontal translation of this segm	0.0 [m]
This segment is	not the reference
Segment Constants File (*.clo)	
File	Generate automatically
Custom Path	C:\Temp\my_constants_file.tlo

Figure 3.4 Cable Configuration settings in PSCAD software [65].

The Cable Interface and Cable Configuration components are linked together through the cable input data that is defined by the user. The cable Interface determines the number of single cables in the system and the conductive layers (conductor, sheath, and armour) in cable design. The groundings for conductive layers (such as the sheath) can also be defined through this component. The Cable Configuration component represents a section of cable line (if the line is indeed sectioned). It determines the cable section length and steady-state frequency. If mutual coupling is taken into account, this can be defined through the Cable Configuration component. The Cable Configuration settings are presented in Fig. 3.4 and the Cable Interface settings in Fig. 3.5.



General	
Cable name	Cable_1
Number of coaxial cables	3
Encompassing pipe conductor is	not present
Segment end specification	sending
External Electrical Connections	
Coaxial cable 1	**conductor/sheath/armour**
Coaxial cable 2	conductor/sheath
Coaxial cable 3	conductor/sheath
Coaxial cable 4	conductor
Coaxial cable 5	conductor
Coaxial cable 6	conductor
Coaxial cable 7	conductor
Coaxial cable 8	conductor
Coaxial cable 9	conductor
Coaxial cable 10	conductor
Coaxial cable 11	conductor
Coaxial cable 12	conductor
Non-electrical Signal Transfer	
Sending Signal Dimension	0
Receiving Signal Dimension	0
Grounding of Conducting Layers	
Ground sheaths with a resistance	No
Ground armours with a resistance	No
Ground outer conductors with a resistance	No
Sheath grounding resistance	0.001 [ohm]
Armour grounding resistance	0.001 [ohm]
Outer conductor grounding resistance	0.001 [ohm]

Figure 3.5 Cable Interface settings in PSCAD software [65].

Cables have a complex layered structure, each having a different electrical and geometrical parameter. These parameters determine the line impedance and results in simulation outcomes. It is evident that the more precisely a cable model is able to respond to the actual system and its parameters, the higher will be the simulation accuracy. In many cases, providing model with efficient data can become a challenging process in itself, such as in terms of a cable systems which already exists, where the data may be missing or detailed data has not been revealed by the manufacturers. The cable structural data that is required for precise modelling is presented in Table 3.2. This table can be taken as a recommendation for TSOs and cable manufactures to simplify the modelling process by having sufficient information available in terms of cable parameters. Another issue is the nominal data which is indeed provided but which is inadequate. Many cases have revealed this to be true, and a study in [5] shows that these deviations between the provided parameters and the real ones have a significant effect on simulation results.

Table 3.2 Full electrical and geometrical cable data for precise cable modelling.

Conductor Data	
Resistivity	Ω·m
Relative permeability	
Inner radius	m
Outer radius	m
Thickness	m
Insulating Layer Data	
Relative permittivity	
Relative permeability	
Outer radius	m
Thickness	m
Inner Semi-Conductive Layer Data	
Thickness	m
Outer radius	m
Sheath Layer Data	
Inner radius	m
Outer radius	m
Cross-section area (entire sheath)	m^2
Number of wires in the sheath	
Wires cross-section area	m^2
Foil cross-section area	m^2
Wire resistivity	Ω·m
Foil resistivity	Ω·m
Outer Semi-Conductive Layer Data	
Thickness	m
Outer radius	m
Outer Covering Data	
Thickness	m
Relative permittivity	

The electrical and geometrical data in the PSCAD cable model for each layer is represented by the cable cross-section in Fig. 3.6, and the input data that is needed by the user is presented in Table 3.3. The real-life cable structure is much more complex than that presented in a PSCAD cable model (or any other EMT-based software).

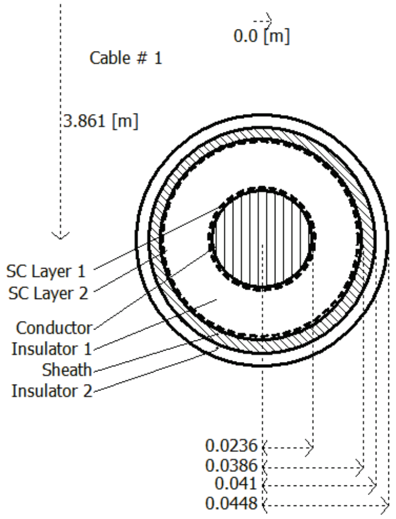


Figure 3.6 Cable cross-section in PSCAD [65].

Table 3.3 Input data for each cable layer (without armouring) in PSCAD cable model.

Core Conductor	
Resistivity	Ω·m
Relative permeability	
Inner radius	m
Outer radius	m
1st Insulating and Semi-Conductor Layer	
Relative permittivity	
Relative permeability	
Outer radius	m
Inner semi-conductor layer thickness	m
Outer semi-conductor layer thickness	m
1st Conducting Layer	
Resistivity	Ω·m
Relative permeability	
Outer radius	m
2nd Insulating and Semi-Conductor Layer	
Relative permittivity	
Relative permeability	
Outer radius	m

Conductor resistivity depend upon the conductor material, the cross-section, and the temperature. Gaining cable core conductor data is usually not a problem, and is provided by the manufacturer at a working temperature. However, the fact needs to be highlighted that the core conductor is commonly composed of wires which are stranded together. This means that the core conductor is not a solid conductor as is considered in the cable model. There are empty spaces between the single wires and therefore the actual effective conductor cross-section is smaller. These empty spaces affect the total core conductor resistivity and this needs to be considered when trying to obtain accurate simulation results.

The correction in conductor resistivity is made by Eq. 3.1 [6]

$$\rho' = \rho \frac{\pi r_1^2}{A_C} \tag{3.1}$$

where ρ' and ρ are the core resistivity being corrected and, before the correction, r_1 represents the conductor radius and A_C core conductor effective cross-section area.

The cable insulation electrical data is provided by the manufacturer in terms of the layer thicknesses. Semi-conductive materials are considered as being part of the insulation layer, with a modification in insulation properties. The semi-conductor thickness is added to the insulation layer and the permittivity is being changed. This is already included in the PSCAD computation process and does not require any additional calculations to be carried out by the user.

The most complex layer in the cable structure is the sheath layer, and its correct modelling needs extra attention. This is one of the main focus points of this thesis and, therefore, it is further discussed in section 3.3, which will include relevant studies.

The mathematical treatment of cable input parameters in PSCAD and the calculation of cable line impedance and admittance matrices are presented in [20], [61]. This thesis will not focus on ground resistance modelling since this is more of a problem for a specific project and one which needs the available data regarding the soil. The grounding resistivity is considered as a constant in the PSCAD cable line model.

Another challenge when modelling cable lines in EMT is the computational time step and simulation speed. The cable line system is commonly divided into sections, so that the sheath cross-bondings and groundings can be carried out along the line when needed. The simulation time step is determined by the length of the line sections (the travelling wave). The shorter the line sections and the higher the number of sections, the smaller is the simulation time step. This means that the simulation compiling time is longer. The implementation of cross-bondings in the cable line model is presented in Fig. 3.7.

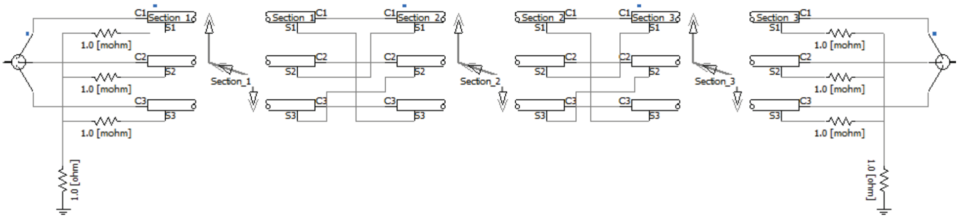


Figure 3.7 The cross-bonded cable line model in PSCAD software [65].

Besides the simulation time step, composing the cross-bonded cable model with several additional connections between the sections and sheaths may also be time consuming for the user. This problem is solved by the additional option of ideal cross-bonding (transposition) in the cable mode, starting with PSCAD v6.2. This option makes compiling the cable model easier and faster for the user. However, this means that sheath transposition is provided by sections that, ideally, are equal. In a real cable system, this is rarely achievable. This simplification is feasible when general network studies are conducted. For more specific cable sheath studies in which the sheath parameter measurements are required, the actual cross-bonding has to be considered and each minor section has to be modelled separately.

3.3 Cable Sheath Modelling

The cable sheath layer is complex, where two conductors of varying thicknesses and various electrical parameters are compounded together. In the EMT cable model, the sheath layer is represented as a single solid layer. The cable sheath's actual design with its two conductive layers and semi-conductive tape between them cannot directly be implemented in the EMT base software. As was presented in Table 3.3, only the resistivity, permeability, and outer radius of the first conductive layer (sheath) can be inserted. Therefore any real cable data needs to be modified and simplified for modelling. Several approaches can be taken when it comes to EMT studies, and these are presented and explained as part of this thesis in [I] and [III].

Each implemented sheath modelling approach is based on the simplification level that has been made in cable sheath representation, from the most simplified to the most complex and detailed sheath layer approach. The simplest method is to entirely exclude the second conductive layer (aluminium foil) in the sheath design and to represent the wired sheath layer as a solid conductor with its nominal resistivity (copper or aluminium resistivity). A more developed sheath layer approach is to correct the nominal resistivity to match the effective area of the wired layer by taking into account the free space between the wires in the sheath design. The most detailed sheath layer approach responds the most to the actual cable sheath design. The wired sheath layer resistivity is corrected with reference to the effective cross-section area and the resistivity of the second conductive sheath layer (aluminium foil) are included in the final value. The latter sheath modelling approach requires detail data and additional corrective calculations to be carried out in sheath resistivity value and the radius, as discussed more in [I] and [III]. This method is not the most effective from the user's point of view, especially when bulky systems are modelled with multiple cable lines being included and, therefore, it is not widely employed in the cable sheath modelling approach being employed in EMT studies. However, the cable sheath has an important role to play in transient situations and, therefore, its contribution to the EMT simulation results was analysed in [I]. The focus in [I] is to evaluate the impact of sheath layer representation in the cable model and the effect of the selected modelling approach upon the entire network area. As the time domain simulations are more in the interest of the TSOs' point of view, the results of [I] are further presented in section 3.3.1.

The mathematical treatment of and comparison between various sheath modelling approaches with impedance characteristics at the frequency domain is a matter that is analysed in [III]. As with the time domain study in [I], sheath modelling is considered from its most simplified approach to the most complex approach.

The results in [I] and [II] indicate that the precision levels for cable sheath presentation in the simulation model has an impact upon the study results. Therefore the most precise sheath modelling approach, when considering both conductive layers, should be preferred in EMT studies. However, for specific network studies in the time domain, the simplified sheath modelling approaches can also supply accurate enough results (section 3.3.1).

3.3.1 The Effect of Sheath Modelling to Simulation Results

Depending upon the availability of input data and the requirements for simulation result accuracy, it becomes essential to estimate the effects of the various sheath modelling approaches on the study results. To be able to clarify the options for sheath modelling and estimate their effect on simulation accuracy, a comparative study was conducted as part of this thesis.

To be able to determine the general and most straightforward effect upon network operation, a transmission system which included cable lines was studied with regard to the various cable sheath modelling approaches. The results of this study are presented in [I], in which network steady-state (power-flow), short-circuit, and lightning surge events were analysed. To be able to assess the effect that originates from the selected sheath modelling approach, the changes to RMS voltage values at the network busses were observed. The variations in voltage values indicated the accuracy of the sheath modelling approach.

The sheath modelling approaches being used in this study are introduced as Cases 1 to 4, where Case 1 is the simplest approach in which the second sheath layer is excluded and the nominal copper resistivity is considered as sheath layer resistivity. Case 2 differs from the previous one by means of incensement (doubling up) in the value of the resistivity, taking into account the free space between the wires. A simple cable layout for Case 1 and Case 2 is presented in Fig. 3.8. Case 3 involves an improved sheath modelling approach, in which wired sheath resistivity is corrected according to the effective cross-section area (Fig. 3.9). As stated, Case 4 is the most detailed sheath approach, in which the compound sheath layer is taken into account and the value for the sheath resistivity is corrected by checking it against both materials. The cable layout for Case 4 is presented in Fig. 3.10. In respect to the treatment for the sheath layer, the layer radius also needs to be corrected, and this is discussed in a more detailed manner in [I] and [III].

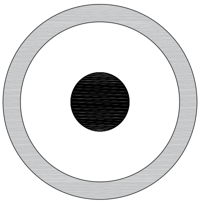


Figure 3.8 The cable layout for the single layer sheath modelling approaches in Case 1 and Case 2.

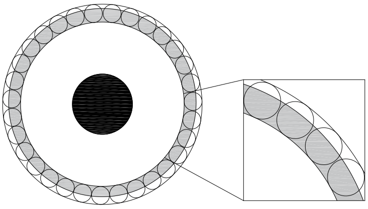


Figure 3.9 The cable layout for the single layer sheath modelling approach in Case 3.

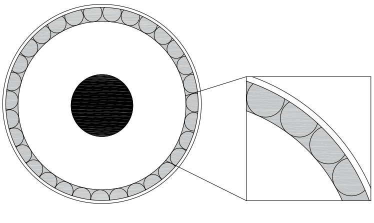


Figure 3.10 The cable layout for double layer sheath modelling approach in Case 4.

Network steady-state results are presented in Fig. 3.11. The network bus voltages are compared to the most precise cable sheath modelling approach (Case 4) in the form of percentage values. Additionally, the results are compared to the cable Pi-model (with no sheath layer) and the PSS/E network results. A similar comparison was carried out in network short-circuit and lightning surge events. Both of these were considered to occur in network Bus 13 (Fig. 3.1), which is connected to the network through the UG cable lines. The short-circuit results are presented in Fig. 3.12, and the lightning surge results in Fig. 3.13.

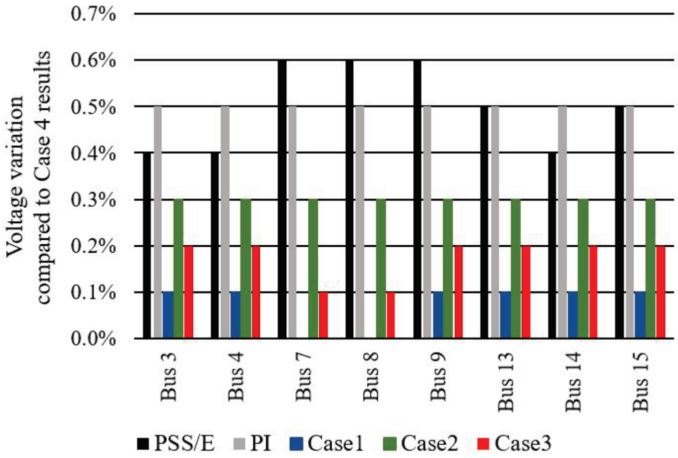


Figure 3.11 A comparison of the network bus RMS voltages when various cable sheath modelling approaches (the Pi-model, Case 1, Case 2, Case 3, and Case 4) are used in a network steady-state situation, with percentage differences against the most complex, Case 4, approach being shown.

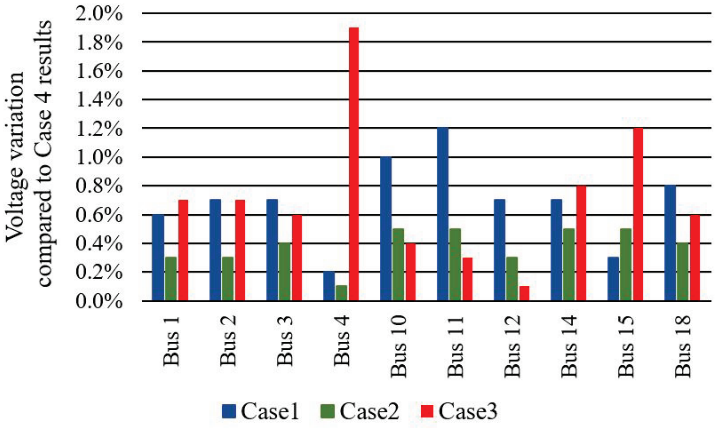


Figure 3.12 A comparison of the network bus RMS voltages when various cable sheath modelling approaches (Case 1, Case 2, Case 3, and Case 4) are used in a network short-circuit situation (Bus 13), with percentage differences against the most complex, Case 4, approach being shown.

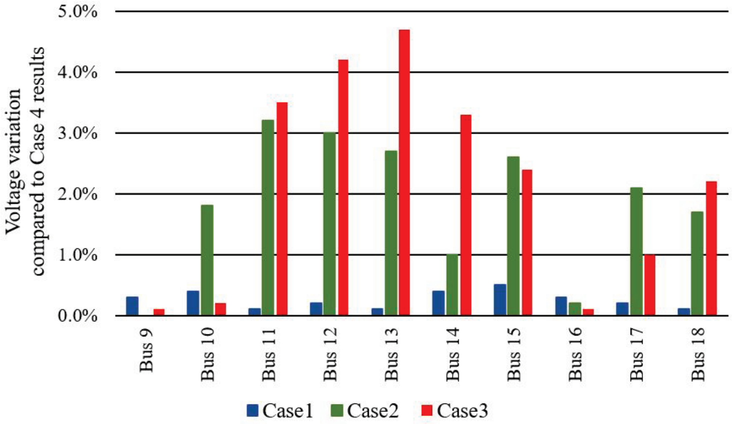


Figure 3.13 A comparison of the network bus RMS voltages when various cable sheath modelling approaches (Case 1, Case 2, Case 3, and Case 4) are used in a lightning surge situation (Bus 13), with percentage differences against the most complex, Case 4, approach being shown.

The study results in [I] and Fig. 3.11 to 3.13 show that the selected cable sheath modelling approach can significantly affect the network bus voltage values in the results. When simple steady-state studies are carried out, the sheath modelling approach will not hold that great a level of importance and the simplistic Case 1 approach can be implemented. However, in transient situations, the precision of sheath layer representation gains a higher level of relevance with the increasing levels of variation in network bus voltage values. If the detailed cable sheath layer modelling becomes inefficient, such as in cases in which there are gaps in the available data, or a level of simulation accuracy being needed, an alternative sheath modelling approach can be used. Based on the studies, when it comes to a short-circuit analysis this can be realised in the form of the sheath modelling approach of Case 2, which provided the closest results to those of Case 4. In terms of lightning studies, it became evident that the simplest case, Case 1, can be implemented as an alternative sheath approach instead of having to use Case 4. Study results showed that Case 1 and Case 4 results are the closest to each other and all other intermediate cable sheath approximations should be avoided. A more detailed discussion on the study results can be found in [I].

In general, the considerable per-unit deviation in a network bus voltages that can appear in relation to the selected cable sheath modelling approach can range up to 5%. This means that, in network studies, the possible 5% deviation in bus voltages in a real network should be considered. This 5% deviation can have great deal of importance when specific studies are carried out, such as those which are related to control systems.

3.3.2 A Study of Sheath Currents and Voltages

Any overvoltage in the sheath layer is a safety hazard for the line equipment, as well as for maintenance personnel. The objective is to reduce the sheath voltage to as safe a level as possible, while at the same time restricting sheath currents in order to reduce line losses and maintain line current carrying capacity. High levels of overvoltage primarily pose a risk to cable joints, as well to the cable insulation. Joints (especially in cross-bonding points) are the most vulnerable parts in the cable line installation and they also significantly serve to increase the risk of line failures. In addition, the risk posed to personnel who are working on the system has to be considered, especially at the cable line terminals, as well as at cross-bonding points when they are housed above ground and are accessible. Increasing the number of cross-bondings along the cable line increases line effectiveness levels and the balance between the phases. It also increases the investment costs and the risk of failures occurring in the cable system.

In many HV networks, it is cross-bonded cable installation that is preferred, since it has an effect both on sheath voltage and current and is therefore considered to be the most optimum solution. However, it raises the question of whether such a complex form of installation is really needed, with its higher levels of investment and maintenance costs and, especially, in urban networks where the line lengths are rather short. To be able to determine which type of bonding method is the reasonable choice and will fulfil the requirements in regard to sheath parameters, if such a thing exists, then specific studies on voltage and current levels are needed. In general, the cable installation method cannot be predefined. The sheath voltages and currents need to be individually analysed and assessed for each cable system arrangement.

Several network aspects need to be considered when it comes to deciding about applicable sheath bonding methods. Evaluating the voltage level in the cable sheath becomes an important topic, especially when non-conventional configurations are being used, such as mixed lines, or cross-bonded cable lines with various lengths between the cross-bonding points. Studies of the network power frequency, as well as of transient situations, are highly important. From the experience that has been gained by utility companies, the lightning surges have been pointed out [37] as having the most essential effect (for cross-bonded installation this is in terms of the surge strike on the phase conductor [66]). In terms of power frequency, for a single point bonded cable installation this lies in single-phase-to-ground faults, and for a cross-bonded installation it covers three-phase or phase-to-phase faults, with both being considered as the most critical circumstances [37]. Calculating sheath voltages and currents is a challenging task that requires sufficient models to be created for the cable system and surrounding network. Using the EMT-based software would be the most reasonable option in resolving these issues. However, it has to be considered that the process of compiling models, as well that of carrying out the computations, are both relatively time-consuming. With the increasing number of cross-bonding points being used and the decreasing length of minor sections being built, the computation time step is decreasing.

To be able to evaluate the choice regarding cable sheath bonding methods for transmission lines with the focus on an urban network (in terms of short cable lines), a study was considered as part of this thesis [II]. A 110 kV mixed transmission line was observed as part of the existing transmission network in urban areas. The principle scheme for the line configuration as part of this study is presented in Fig. 3.14.

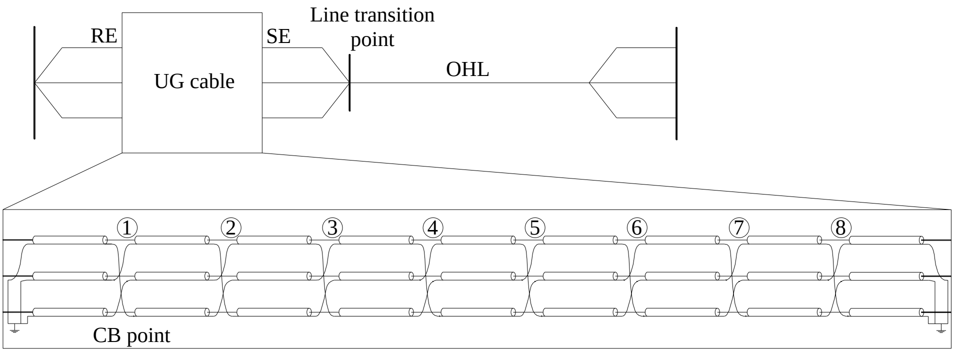
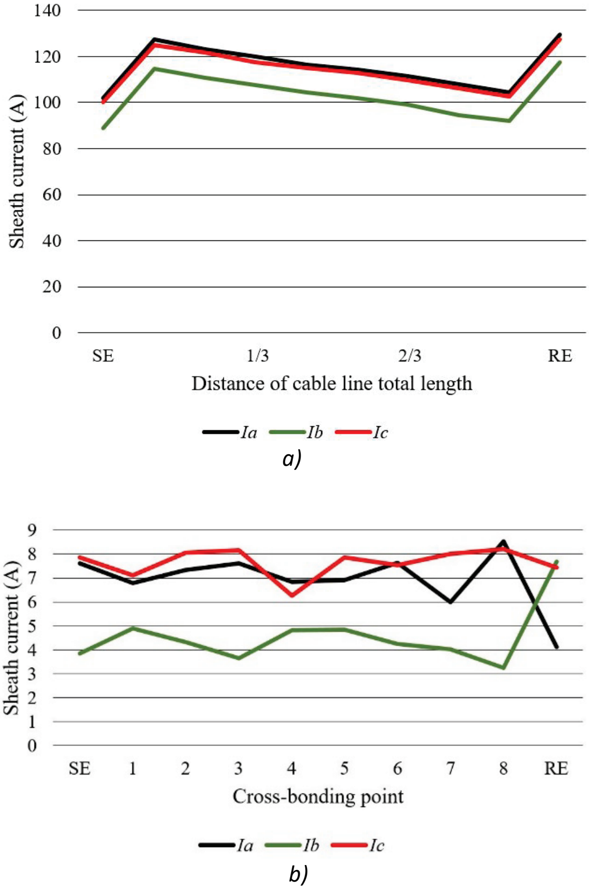


Figure 3.14 The principle scheme for a 110 kV mixed transmission line as part of this study with eight cross-bonding (CB) points in the cable line installation [II].

The sheath voltages and currents in the cable line itself were analysed and compared for two of the most commonly applied sheath bonding methods: both ends bonding and (continuous) cross-bonding with eight cross-bonding points (Fig. 3.14). The proportion of OHL and UG cable line in the mixed line is 3.2 km and 3.7 km respectively. The network steady-state, single-phase-to-ground fault in the cable line receiving end (RE), and lightning-related situations were all analysed.

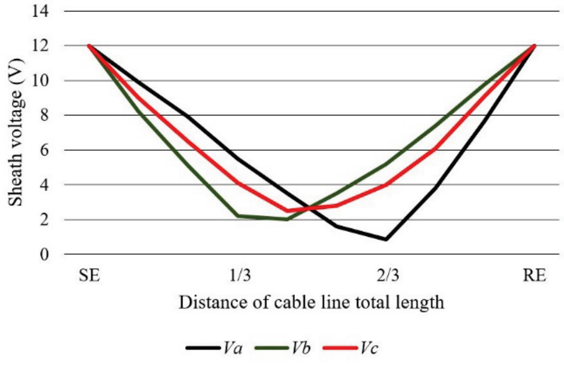
The results for network steady-state conditions show that implementing a cross-bonded cable installation will have a great deal of reducing effect on the sheath current value (around 93%) when compared to both ends bonded cable installations (Fig. 3.15). Overall, whether both ends bonded or cross-bonded cable installation is used, there is no notable change in the sheath voltage level in steady-state conditions (Fig. 3.16). There are some cross-bonding points in the line for which the sheath voltage is slightly higher, but this is lowered after every third section by means of the sheath cross-bonding balancing effect.



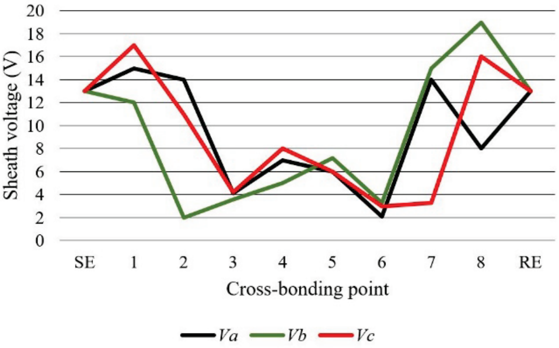
a)

b)

Figure 3.15 Sheath currents for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation in a network steady-state situation.



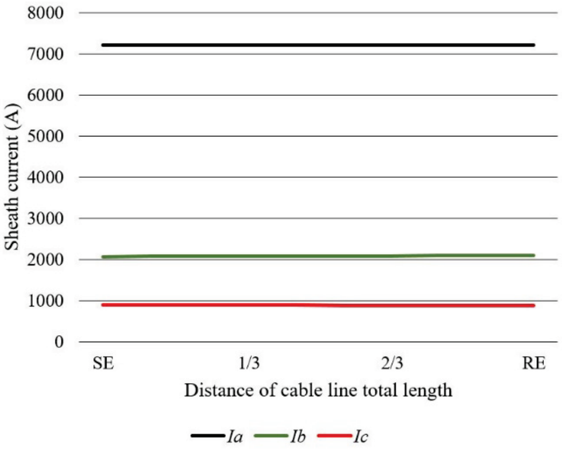
a)



b)

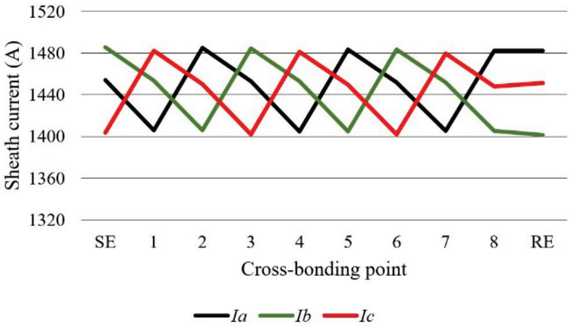
Figure 3.16 Sheath voltages for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation in a network steady-state situation.

In a single-phase fault situation in the cable line at the RE end, cross-bonding the cable sheaths will reduce sheath currents by around 80% when compared to a both ends bonded cable installation (Fig. 3.17). For the sheath voltage level, there is no major difference between the two sheath bonding methods (Fig. 3.18).



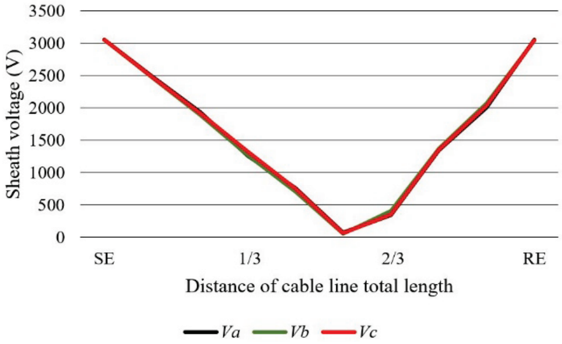
a)

Figure 3.17 Sheath currents for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation in a single-phase-to-ground fault in the cable line at the RE end.

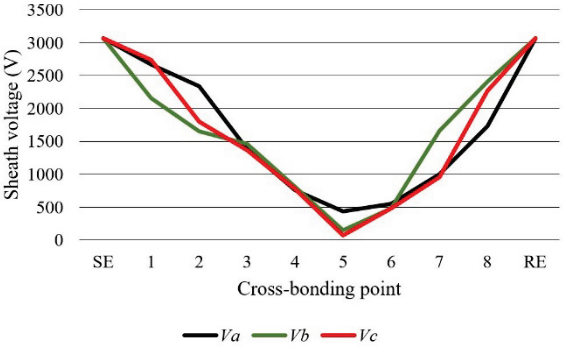


b)

Figure 3.17 Sheath currents for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation in a single-phase-to-ground fault in the cable line at the RE end (continued).



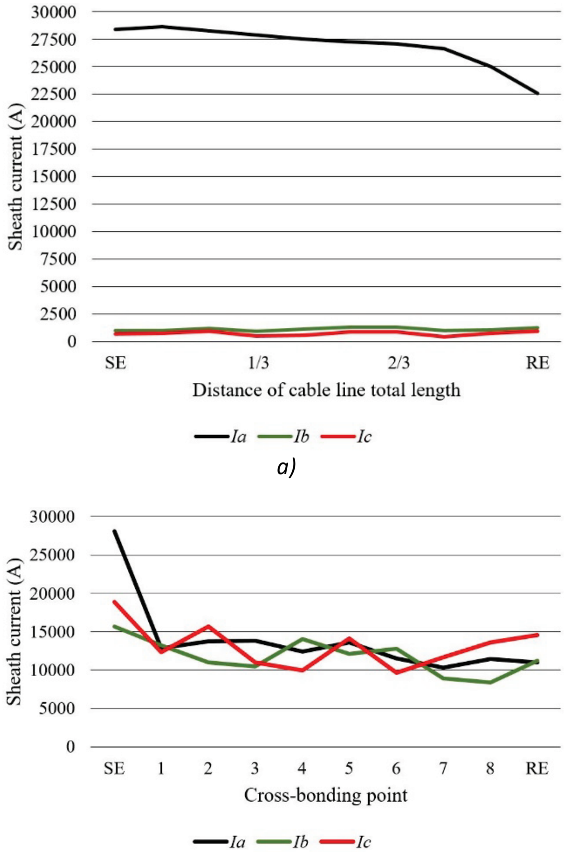
a)



b)

Figure 3.18 Sheath voltages for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation in a single-phase-to-ground fault in the cable line at the RE end.

A lightning study in relation to OHLs showed that cross-bonding cable sheaths will not reduce the sheath current value. On the contrary, the currents in all three phases were more similar, with an increasing current value in two non-faulted phases: phase *a* and phase *b* (Fig. 3.19). Comparing the sheath voltage level between both ends bonded and cross-bonded cable installations, the result was that cross-bonding cable sheaths will deliver higher sheath voltages along the line in cross-bonding points (Fig. 3.20).



a)

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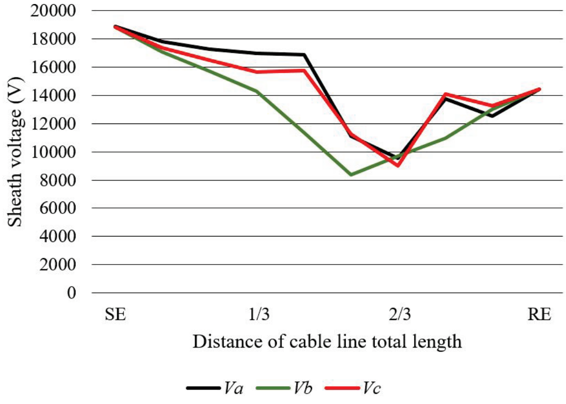
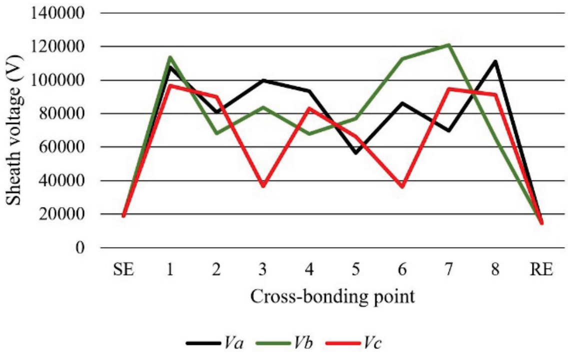
Figure 3.19 Sheath currents for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation for a lightning-related situation.



a)

Figure 3.20 Sheath voltages for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation for a lightning-related situation.



b)

Figure 3.20 Sheath voltages for a three-phase cable line system with a) both ends bonded and b) a cross-bonded sheath installation for a lightning-related situation (continued).

The sheath voltage level for network steady-state conditions will not become an issue, regardless of whether a both ends bonded or cross-bonded cable installation is being implemented, since the sheath voltage value will not reach levels that can be of any concern (restrictions in the value of the sheath voltage were discussed in section 1.2.2).

In the case of transient events taking place in a network (such as faults and lightning strikes), the induced voltage in the sheath layer needs to be limited by additional mitigation methods (such as SVLs) to protect the cable line insulation and equipment. Cross-bonding the cable sheaths will not have an improving affect for the cable sheath's voltage level in such situations.

When the cable sheath's current level is of interest, implementing cross-bonding in cable installation instead of both ends bonding will significantly reduce the sheath current levels for a network steady-state and instances of faults; thereby increasing cable line effectiveness levels. However, during lightning strikes cross-bonding will not have an effect on the cable sheath's current level.

Therefore, with relatively short cable line lengths, implementing sheath cross-bonding is profitable when there is a relatively high demand for reducing line losses that may be caused by the sheath current, and the current value needs to be suppressed. However, in meshed urban networks, the transmission lines may often be under-loaded and/or over-dimensioned. Therefore the line loading levels should first be analysed to determine whether cross-bonding installation may be needed. Overvoltages in the sheath layer need to be limited by mitigation methods in transient situations regardless of which cable line installation method is being implemented.

3.4 The Number of Cross-Bonding Points

In situations in which a cross-bonded cable installation is preferred, the question will arise regarding optimum cross-bonding points. The higher is the number of cross-bonding points, the more currents will be suppressed in the sheath layer and the higher will be the level of system effectiveness being achieved. This also means that the length of line sections between the cross-bonding points has to be equal, otherwise an unbalance between the phases will be created. On the contrary, the increasing number of cross-bonding points means higher investment costs, raising the need for maintenance and bringing along with it a higher risk of failures occurring. Therefore the optimum number of cross-bonding points along the line becomes an essential factor. It is evident that the longer the cable line may be, the higher may be the number of required cross-bonding points along the line. In short cable lines, determining the optimum number of cross-bonding points is not quite so foreseeable.

The purpose of part of this thesis is to assess the optimum number of cross-bonding points when considering the effectiveness levels of the system's operations. The impact that increasing the number of cross-bonding points will have upon cable sheath voltage and current levels was analysed and presented in [II]. It could be seen that implementing a higher number of cross-bonding points along a cable line is not always justified. The network and cable line system was considered as being the same, as described in the previous section 3.3.2 in Fig. 3.14, with the difference being that a total of three cable line configurations were compared, with eight, five, and two cross-bonding points (with an equivalent set-up of nine, six, and three minor sections in the cable line). The sheath current and voltage values were compared at the network steady-state and during an OHL lightning-related event (as this was found in section 3.3.2 to be the worst-case scenario).

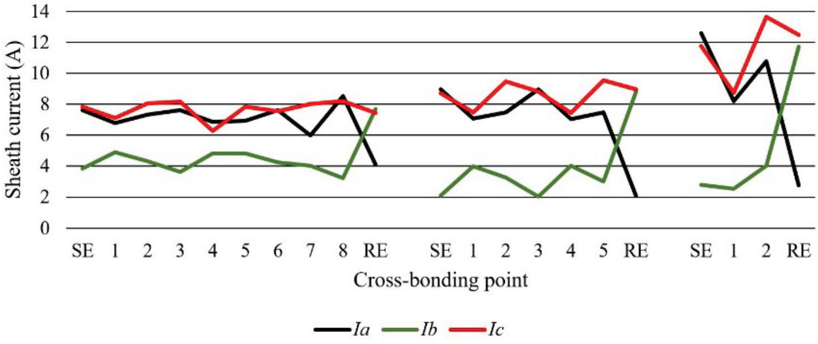


Figure 3.21 Sheath current maximum values for a three-phase cable line system with eight, five and two cross-bonding points in the cable installation in a network steady-state situation.

The number of cross-bonding points will affect both sheath current and voltage levels. The results show that in network a steady-state condition there is no significant difference in sheath currents (Fig. 3.21) and voltages (Fig. 3.22) when cable line cross-bonding points are decreased from eight to five.

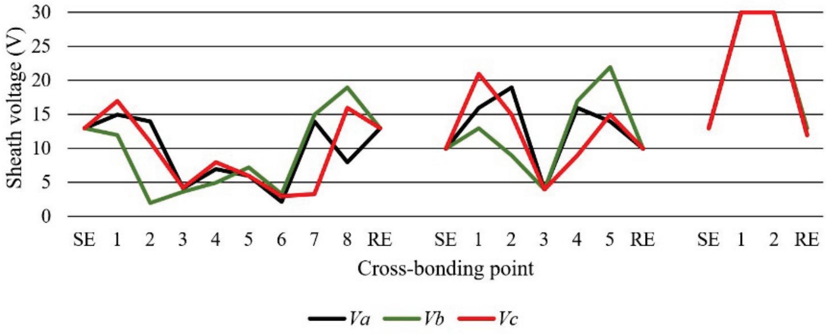


Figure 3.22 Sheath voltage maximum values for a three-phase cable line system with eight, five and two cross-bonding points in the cable installation in a network steady-state situation.

When cross-bondings along the cable line are decreased to two in number, there are more noticeable changes in sheath current and voltage values. The sheath currents are more unbalanced and the maximum sheath current value increases by 5 A when compared to a cable installation with eight cross-bonding points. With only two cross-bonding points, the sheath voltage along the cable line increases significantly and reaches as high as a value of 30 V, but in cable line terminals, the sheath voltage remains at the same level with a cable installation using eight cross-bonding points.

The OHL lightning study results show that sheath current value (Fig. 3.23) is not related to the number of cross-bonding points along the line. In addition, there is no effect on sheath voltage level (Fig. 3.24) at cable line terminals, which is a result that remains the same for all three of the line configurations being studied. The only impact that can be seen from the lightning-related event study is the increasing sheath voltage in cross-bonding points along the line when the number of cross-bondings is reduced to the minimum number of two. In this case, the maximum sheath voltage value at the cross-bonding point increases to 31 kV when compared to a cable installation with eight cross-bonding points.

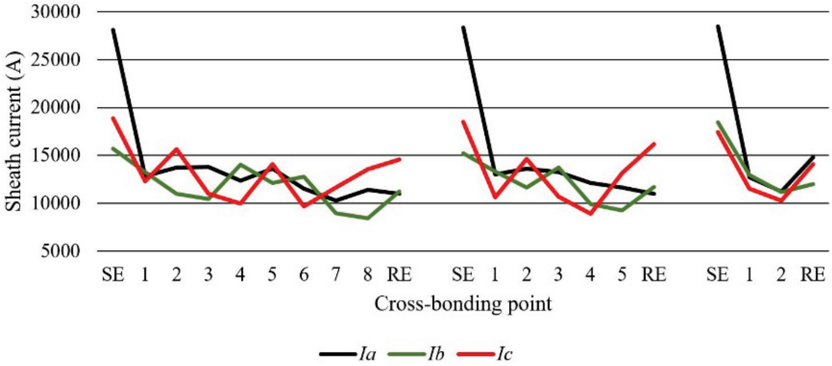


Figure 3.23 Sheath current maximum values for a three-phase cable line system with eight, five and two cross-bonding points in the cable installation during a lightning-related situation.

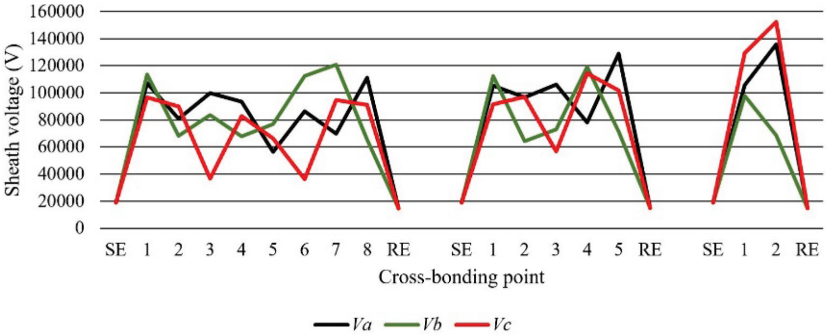


Figure 3.24 Sheath voltage maximum values for a three-phase cable line system with eight, five and two cross-bonding points in the cable installation during a lightning-related situation.

Based on the study and results that have been presented [II], a higher number of cross-bondings is not always something that can be considered as being reasonable, and will not improve the cable system’s operations. With short cable lines, the minimum number of cross-bondings will be sufficient from the line operational perspective.

With the corresponding line length being around 4 km, the optimum number of minor cross-bonding sections would be three.

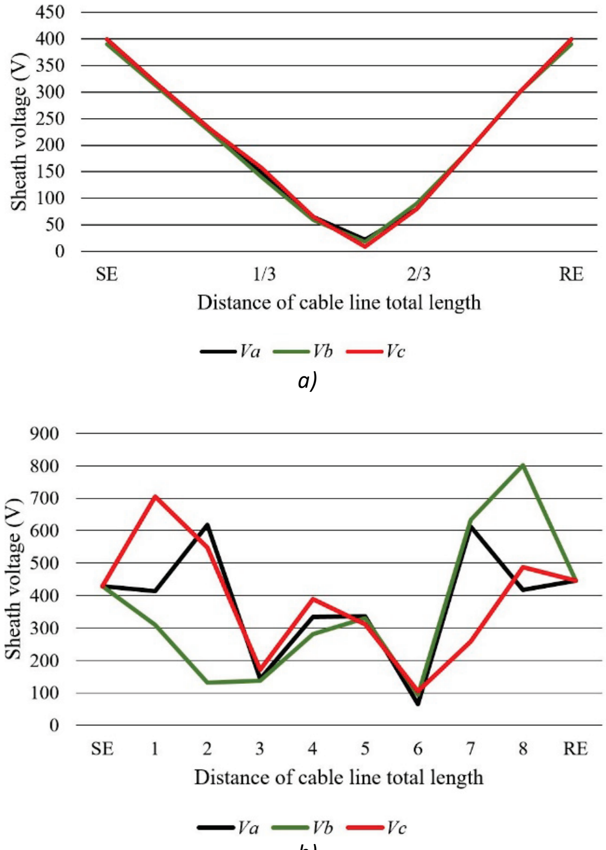
3.5 Mixed Line Study

Transmission lines that consist partly of a UG cable line and partly of an OHL experience a change in the impedance value at the line transition point. The variation in the impedance value affects mixed line operations, especially in transient situations (regarding the speed of the travelling wave, and through refractions and reflections in the wave). When a lightning-related event takes place in relation to the OHL, the transient wave penetrates into the UG cable line itself, resulting in stress and high overvoltage values in that UG cable line. Mixed lines in a network require extra attention.

The maximum transient voltages in a mixed line are studied in [1], where line energising and re-strike transient phenomena were considered. It was discovered that the worst-case scenario appears when a surge wave travels from the cable line itself into the OHL, since there occurs a magnification in the voltage value. These occasions in a network are rare or almost non-existent. When the surge wave travels in the opposite direction, from the OHL into the cable line, the voltage peak value decreases. However, due to the reflections and refractions in the surge wave, the voltage's peak value can still be higher in comparison to the full cable line configuration, especially in cross-bonded installations. The results in [1] also showed that the peak voltage at the mixed line receiving end is strongly related to the share of cable line and OHL sections in the mixed line's total length. The highest voltage value appeared when the cable and OHL lengths were installed at a ratio of 1:2 respectively.

If a cable line is cross-bonded, there are additional reflections and refractions which occur in the cross-bonding points. Therefore the voltage peak values in the cable line cross-bonding points along the line can be higher than they are in line terminals. As part of this thesis, this phenomenon was analysed on a mixed line (Fig. 3.14) which was part of a 110 kV transmission network. The total length of the line under the study is about 7 km, with an equal ratio of OHL and UG cable line. The three-phase-to-ground fault and the lightning-related event on the OHL part of the system were both considered, and the overvoltage value which appeared in the UG cable section was observed for both ends bonded and cross-bonded cable line installations.

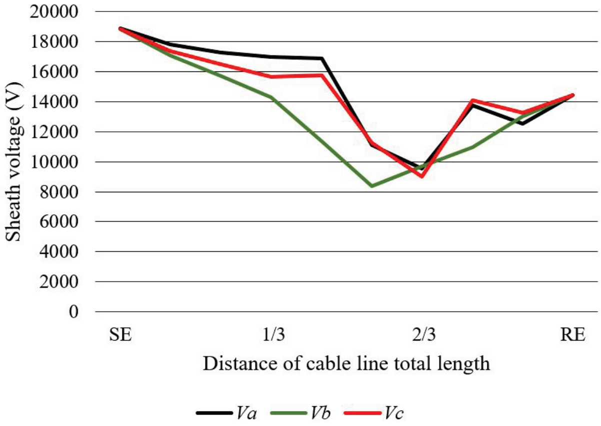
The results for the OHL fault situation are presented in Fig. 3.25. It can be seen that if a both ends bonded installation is implemented, the highest voltage value appears at the line terminal points, at the sending end, and at the receiving end. When cable sheaths are cross-bonded, the voltage values are higher in cross-bonding points with a significant excess of voltage value when compared to terminal points. The sheath overvoltage values in an OHL lightning-related situation are expected to be higher and are presented in Fig. 3.26. If a cable line is bonded in both ends, then the sheath overvoltage peak value appears at the mixed line termination point (SE) and the sheath overvoltage decreases with the distance along the cable line. If the cable line is cross-bonded, the overvoltage in the line terminals reaches the same level as a both end bonded line installation. However, in cross-bonding points along the line, the sheath overvoltage is significantly higher.



a)

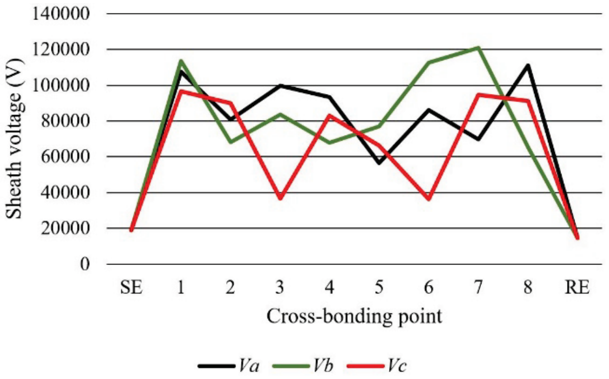
b)

Figure 3.25 Cable line sheath voltage levels in a) a both ends bonded cable installation and b) a cross-bonded cable installation in an OHL's three-phase-to-ground fault situation with a mixed line configuration.



a)

Figure 3.26 Cable line sheath voltage levels in a) a both ends bonded cable installation and b) a cross-bonded cable installation in an OHL lightning-related situation with a mixed line configuration.



b)

Figure 3.26 Cable line sheath voltage levels in a) a both ends bonded cable installation and b) a cross-bonded cable installation in an OHL lightning-related situation with a mixed line configuration (continued).

The results that have been presented prove that transient voltages which originate from OHLs do not only penetrate into the cable line itself, but can reach significantly higher peak values along the cable line in cross-bonding points. These overvoltages may damage the cable system if that system is not properly designed. A cable insulation will fail when it comes under excess stress, and cross-bonding points - the most vulnerable part of the cable system - may be damaged. When mixed lines become present in a network, extra attention should be paid to the potential for disturbances which may originate in OHLs but which may influence cable line operations. Specific studies to determine the overvoltage values and mitigation methods are required in order to protect the cable line and the network operation.

3.5.1 The Location of Transient Event

The network's response to a transient event is dependent upon the transient event's location, due to the network's configuration and its characteristics. Some parts of the network are weaker or more sensitive than others, and they can respond to transients more seriously. Therefore the location of a transient situation has an importance for the entire network operation. In the following, the occurrence of a transient event in various places along a mixed line has been analysed. A lightning surge through the OHL part is considered at two locations (Fig. 3.24), close to line transition point and at the other end of the OHL. The lightning event impact upon the UG cable line itself has been observed. The UG cable sheath is cross-bonded with eight cross-bonding points, and the sheath voltage and current values were observed and were compared to the corresponding two different lightning locations on the OHL section.

In Fig. 3.27, Location 1 represents the lightning surge through the OHL sending end (the OHL substation side of the network), and Location 2 at the OHL receiving end, close to the transition point between the OHL and the cable line. With respect to the cable line, Location 1 represents the furthest occurrence of the transient event and Location 2 is the closest. The difference between these two lightning locations in terms of distance is 3.2 km. It is presumed that the closer is the transient occurrence to the transition point, the higher will be the impact upon the cable line's operations.

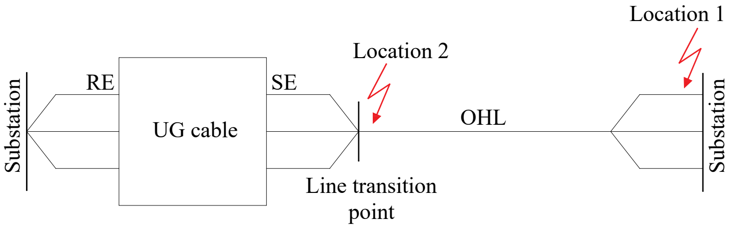
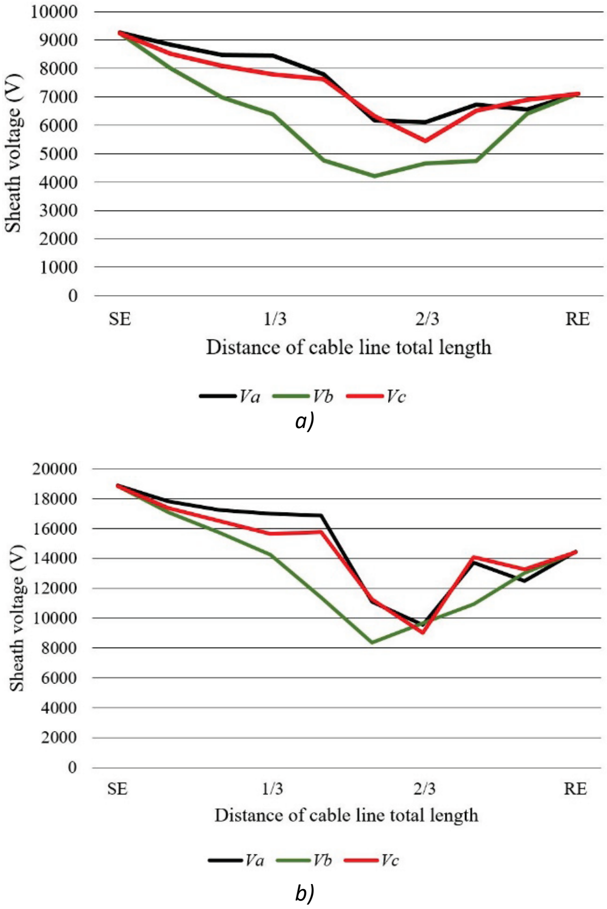


Figure 3.27 Lightning surge events (locations 1 and 2) in a mixed line configuration.

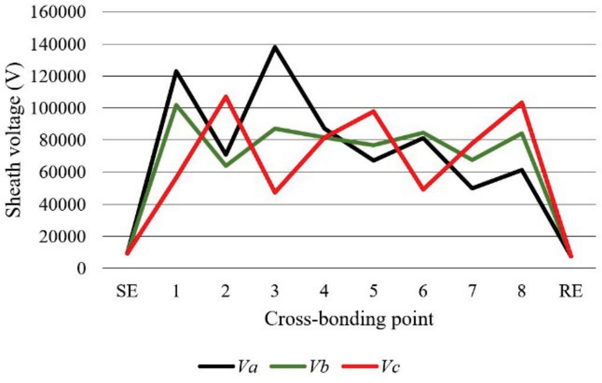
The cable sheath voltage values in respect to the two different transient locations with a both ends bonded cable installation are presented in Fig. 3.28. The results clearly show that a transient lightning event which could penetrate into the cable line would be higher if the lightning surge were to occur closer to the cable line in Location 2, where the voltage peak value is roughly double when compared to the peak voltage results at Location 1. When the cable sheaths are cross-bonded as in Fig. 3.29, the differences between the results for locations 1 and 2 are not particularly evident.



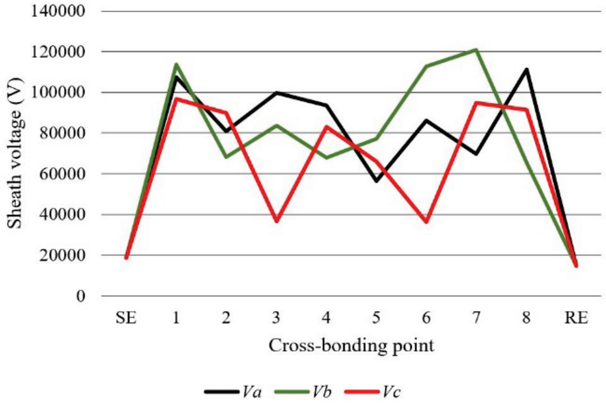
a)

b)

Figure 3.28 Sheath voltages for a both ends bonded cable installation in an OHL lightning-related situation at a) Location 1 and b) Location 2 in a mixed line configuration.



a)

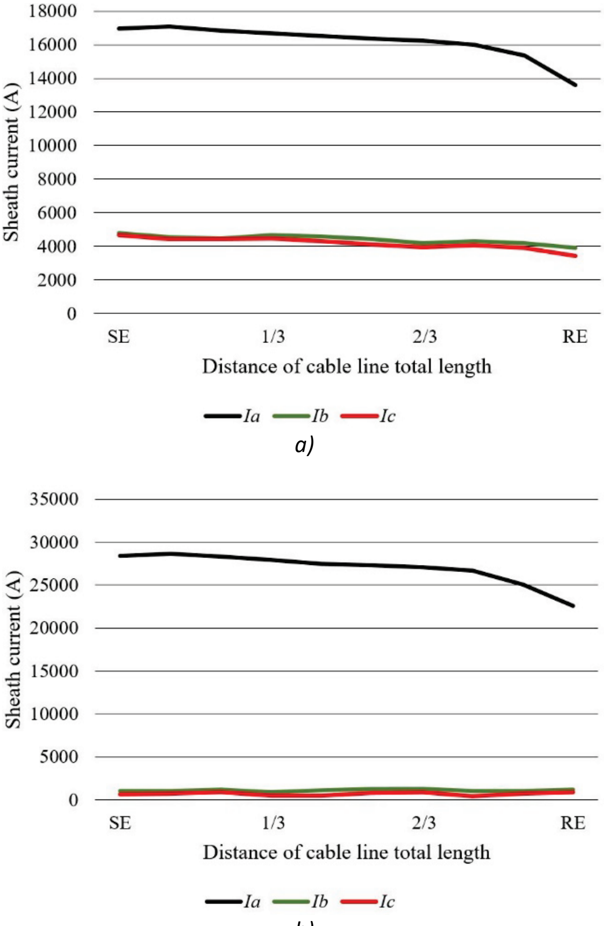


b)

Figure 3.29 Sheath voltages in a cross-bonded cable installation in an OHL lightning-related situation at a) Location 1 and b) Location 2 in a mixed line configuration.

Overall, there is no major variation in cable sheath voltage levels, whether the lightning-related event occurs at Location 1 or Location 2. With an exception being some of the cross-bonding points (such as cross-bonding points 1 and 3 in Fig. 3.29a), where the sheath peak value can reach higher values when the OHL lightning-related event takes place at the farther point (Location 1) from the cable line.

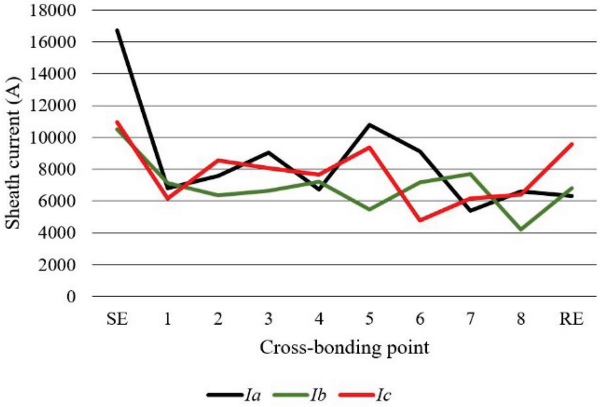
The sheath currents have been analysed for the same situation. Fig. 3.30 presents the results for a both ends bonded cable installation. It can be seen that when a lightning strike occurs closer to the cable line in Location 2, the sheath's current value in the faulted phase *a* is significantly higher when compared to the results for Location 1. The same conclusion stands for a cross-bonded cable installation, where the results in Fig. 3.31 indicate that the sheath's current peak value at the sending end, as well as along the cable line, reaches a significantly higher level when the lightning strike takes place close to the termination point at Location 2.



a)

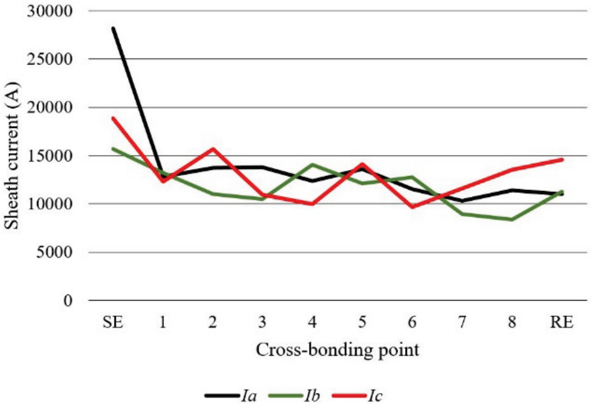
b)

Figure 3.30 Sheath currents for a both ends bonded cable installation in an OHL lightning-related situation at a) Location 1 and b) Location 2 in a mixed line configuration.



a)

Figure 3.31 Sheath currents in a cross-bonded cable installation in an OHL lightning-related situation at a) Location 1 and b) Location 2 in a mixed line configuration.



b)

Figure 3.31 Sheath currents in a cross-bonded cable installation in an OHL lightning-related situation at a) Location 1 and b) Location 2 in a mixed line configuration (continued).

It can be concluded that the location of the occurrence of any OHL lightning-related event along a mixed line has a significant impact upon a cable line operation. The closer to the line termination point the lightning strike occurs, the higher is the transient current circulating in the cable sheath and the higher is the sheath overvoltage. Additionally, in the case of a cross-bonded cable installation, the peak voltage values along the cable line at the cross-bonding points can reach higher values when a lightning-related event occurs further along the OHL. This phenomenon is the result of various reflections and refractions in the surge wave and their superpositions, which again indicates how individual line studies are required for this type of phenomena.

3.6 Network Modelling Area

Transmission networks are large and bulky systems. Modelling complex systems that include large number of nodes (buses) can become highly challenging since the simulation running time is higher, as is the time spent on designing the simulation model. It is effective to keep the modelling area as compact as possible but, at the same time, achieve accurate results and receive the required information from the network simulation. It becomes important, especially from the TSO point of interest, not to exclude network nodes that may be affected by any transient phenomena or to display any other important information about network operations.

The most common method being used for large networks is to determine the network area (or line) that is of interest and then to model the rest of network as system equivalents. This means that system short circuit impedances are calculated at a steady-state frequency. In model form, any voltage source with an RL impedance is applied at the network boundary buses. This method will not provide the most accurate results possible. The system equivalent impedance at the borderline buses is lower than is the impedance of those lines that are connected to the same buses in a real network [1]. This leads to potential deviations in simulation results, since the reflected wave magnitude in a simulation is larger than it is in a real system. The system equivalents should be modelled along a certain distance (the modelling depth) from the line or network area that is under focus.

The modelling depth for cable line and OHL studies is different because the line characteristics are different. In mixed networks (lines), any estimation of modelling depth becomes even more difficult due to the reflections and refractions at the line transition points and the difference in transient damping. This problem is discussed briefly in [1]. It is not clear how far nodes in the network should be modelled in order to be able to gain enough information and obtain accurate results.

As part of this thesis, one of the objectives was to analyse the network modelling area specific to cable lines and mixed lines. For this purpose, the 110 kV transmission network was studied in [I]. The configuration of the network is presented in Fig. 3.1. The cable lines that were included in the network are modelled using the most detailed cable sheath modelling approach (Case 4) (section 3.3).

In order to be able to estimate the network modelling area, the network bus voltage levels were analysed during the network steady-state and during a lightning-related event. The results are presented in [I] and in the following Fig. 3.32. The interest here is in observing how far a point in the transmission network the lightning transient event penetrates and what is the relation of the penetration depth regarding OHLs and UG cable lines. This provides information about the modelling depth requirements for networks with cable lines. Bus voltages are analysed with regard to bus levels (zones) in the network, indicating how far the corresponding bus is located from the lightning-related event at Bus 13 in the network.

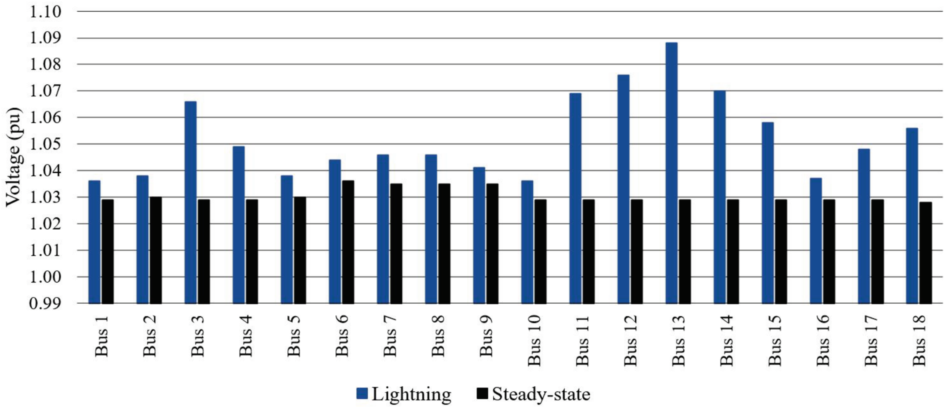


Figure 3.32 Simulation network bus voltages during a lightning-related event on Bus 13 and network steady-state operations.

Bus 13 is connected to the neighbouring buses only through the cable lines. The study results in [I] and Fig. 3.32 show high overvoltage penetration into the neighbouring first level buses (Bus 4, Bus 12, and Bus 15). When observing the voltage value at second level buses (Bus 5, Bus 11, and Bus 16), it can be seen that Bus 11 which is connected through cable line has a high voltage value, while buses which are connected through OHLs (Bus 5 and Bus 16) do not. A more detail discussion of the study and results can be found in [I].

In general the study results show that, for cable networks or networks which include cable lines, the modelling area being considered needs to be wider when compared to OHL networks. In many cases, OHL networks are eligible for being modelled up to the second or third level buses. With cable lines, the transient voltage penetration can be seen even as far as the fourth level buses. Estimating the cable network modelling area is more complicated, and study results in [I] showed that the sensitivity of the network modelling area to transient events depends upon the number of cable lines that are present, as well upon the total length of the cable lines. The higher is the share of cable lines and the longer is their total length in a network, the higher will be the levels of sensitivity, and a wider modelling area should then be considered.

3.7 Recommendations for Cable Modelling and Network Analysis in Transmission Networks

The work presented in this thesis and in publications [I]-[III] shows that the planning and analysing of cable lines (networks) is a complex task. It has also been confirmed that, for the purposes of being able to study HVAC cable lines or transmission networks which include cable lines, no generalisations can be made that can be based on previous studies regarding other networks. Each project which involves HVAC cable lines (networks) requires an individual approach. Specific transient phenomena are strongly related to the network configuration and interaction between the network elements. As well as this, cable line operations and responses to transients is highly dependent upon the line parameters, the line's length, and the installation method that has been used. In addition, and in relation to studies on cable lines (networks), any extensive network needs to be included in the analysis. Modelling and analysing only one specific part of a cable line (such as that part of it which is still being planned) is not sufficient when it comes to any hopes of being able to obtain sufficient results, and the surrounding network should also be included in any EMT studies. To be able to ensure the cost-effective planning of a cable line (network) and then its installation, and ensuring reliability, protection, and safety, individual studies and analyses are required for the network configuration.

Based on the analysis and discussion presented in previous sections of this thesis, a general cable network modelling and analysis methodology is proposed, which provides help to transmission system operators when it comes to estimating the extent of cable network modelling in terms of network planning. Its overview is presented in Fig. 3.33.

The objectives behind network studies (or part of network) are mostly originating from the interests of network operator. Study objectives have a role defining the cable network modelling process by being closely related to network characteristics, data collection and correct cable modelling approach.

For network or its part under the interest, it is essential to first define the configuration and characteristics of the network, e.g., defining the share of cable lines and mixed lines, with their lengths and installation methods. The higher share of cable lines in the network will lead to greater demand on high frequency network studies. With cable lines, the transient phenomena can have greater consequences compared to OHLs (section 1.1.3). When mixed lines are present in network, the OHL transient events should be included (section 1.3 and Chapter 3). Long cable lines will include the transient phenomena related to grater capacitive component in network and need extra attention Chapter 2).

When the characteristics of the network under the interest have been defined, the requested data collection is followed. The simulation results accuracy and needed level of detail in cable design parameters is also defined by the study objectives. For general networks and simple steady-states studies, the cable design can be simplified (Publication [I] and Chapter 3). In those cases the simple cable geometrical and electrical parameters are needed, such as each layer overall thickness and material nominal resistivity. However at high frequency or specific cable line studies (such as studies related to sheath layer), more detailed cable design presentation is needed. The each layer and material real thickness and effective resistivity needs to be considered. For TSOs, the latter means that manufacturers have to provide the cable full electrical and geometrical data (according to Table 3.2). If the exact data is not available (most often related to sheath layer), then a certain deviation in general study results can appear, especially when specific sheath related (e.g., faults and lightning-related events) studies are conducted.

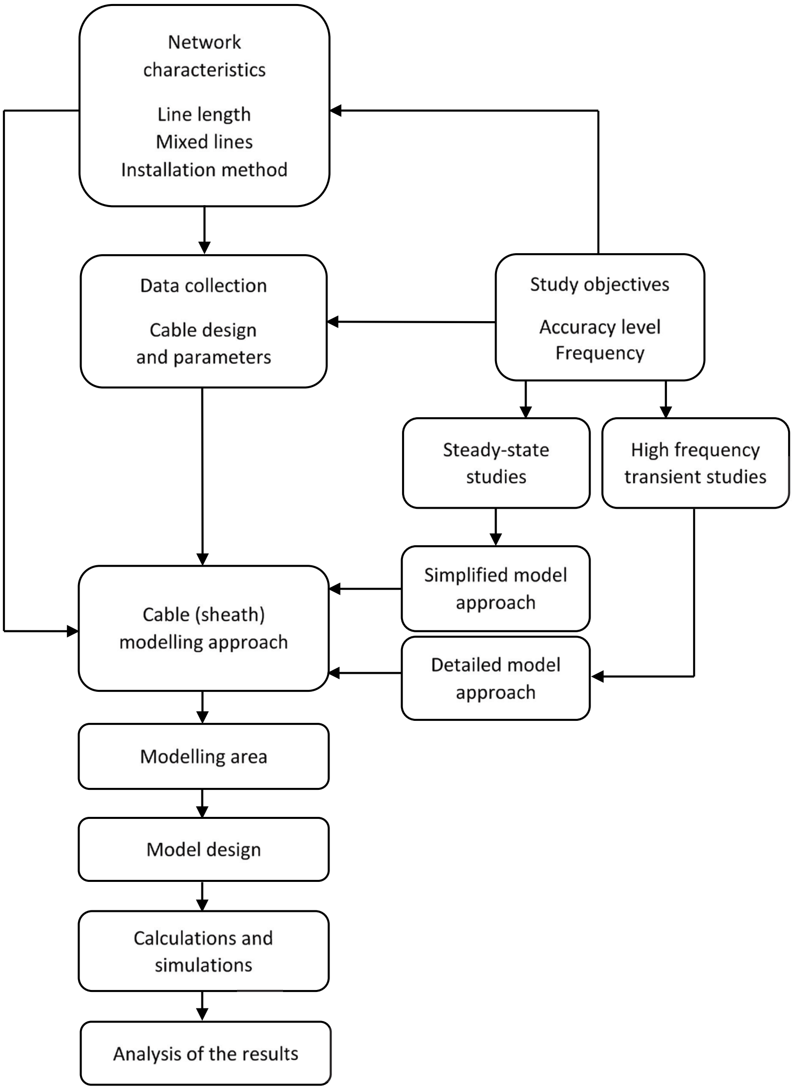


Figure 3.33 The cable network modelling methodology.

Based on the study objectives and the available cable parameters, the correct cable sheath modelling approach has to be chosen (Publication [I], [II] and section 3.3). For steady-state studies, the simplified approaches can be used. At higher frequencies and with higher demand on results accuracy (e.g. studies related to control systems), the complex sheath modelling approach should be chosen. If not, then a deviation in simulation results have to be take into account.

When the network characteristics have been defined and the study objectives with their accuracy rate and correct cable modelling approach have been determined, the needed extent of the network modelling area can be analysed. Networks with a higher share of cable lines require a wider network modelling area, especially when high frequency studies are being conducted (Publication [I] and section 3.6).

Once all of the previous is considered and input data have been gathered, then the corresponding network model can be designed for the subsequent network simulations and analysis. Depending upon the network characteristics, the work of designing the network model can be time-consuming. The middle way for modelling a cable network (or mixed network) would be to consider a higher level of detail (such as sheath layer presentation, or the cable installation method) at the specific transient event location in the network, and to simplify the modelling (such as using the alternative sheath modelling approach, or enabling cable model simplifications in the model, such as in terms of ideal cross-bonding) at the farther network points. This will provide accurate results which are closer to the event and show some level of penetration impact into the rest of the network. The special attention to modelling details is needed when dealing with mixed lines and cable lines including cross-bondings. At network transient events, these will have significant impact to the behaviour of overvoltage wave and therefore to the simulation results.

Summary

There are changes taking place in transmission networks, where conventional OHLs are under consideration for being replaced by UG cable lines. Several TSOs have taken a firm standpoint, deciding not to build any new transmission lines in the form of OHLs and many more are continuing to investigate this standpoint. Estonian TSO is also considering the replacement of conventional OHLs in urban areas with UG cable lines, which is a subject that has driven the need for analysis as presented in this thesis.

The focus of this work is more precisely pinpointed on meshed networks with rather short transmission lines, with these being considered as being more characteristic of urban areas. This type of transmission network has not received much research interest so far. The issues that have appeared in characterised networks are different from those which have appeared in specific projects that are related HVAC cable links (these are typically long cable connections between large systems), where several studies have been published in the available literature.

With the increasing number of cable lines in the transmission network, a wide-ranging analysis is needed, this being important for TSOs in network development and planning. The electrical behaviour and installation methods being used between OHLs and UG cable lines are significantly different. These aspects need to be considered when deciding about line technology and being discussed in the first chapter. As well with the consideration to the variations in line installation methods, along with their impact and cost-effectiveness. The final part of this chapter deals with additional aspects that are relevant to cable networks (lines) which may need extra attention in transmission networks. As well as this, the subject of mixed networks (lines) one that is being emphasised as it cannot be avoided in the line technology transition process.

The second chapter in the thesis focuses on the EMT phenomena in HVAC networks and analysis specific phenomena which are related to cable line installations, usually due to the higher capacitive component. Here, the most relevant transient events and studies that have been drawn from the interest of TSO are defined, which correspond to mesh transmission networks that include OHLs and cable lines which are of relatively short lengths. The worst-case scenarios are described.

The third chapter is devoted to the modelling and analysis of the cable model and network. Cable modelling principles in EMT software are being introduced with a focus on the presentation of the cable sheath layer. The cable sheath layer was modelled by implementing various approaches, and an analysis of its effect on the network simulation results was also shown. From line operation aspects, it is important to identify the level of circulating currents and induced voltages in the cable sheath. To be able to analyse the effectiveness of cable line installations and the methods used to implement them, the cable line sheath currents and voltages are modelled by basing them on a real 110 kV network. A cable line with a both ends bonded and cross-bonded installation as part of a mixed line was taken under consideration. The optimum number of cross-bondings along the cable line were also analysed. The final part of this chapter investigates the optimum network modelling area that needs to be considered when cable lines are part of the network. From all of the cable network study aspects, several recommendations were provided for TSOs.

Contributions

The objective of this research was to provide more clarity in the cable and its sheath modelling for EMT studies from the perspective of TSO. Chapter 3 of this thesis and publications [I], [II] focus on this matter and present an analysis and discussion on alternative sheath layer modelling approaches. From the point of view of the practical aspects, to be able to model compound sheath layer in the EMT-based software, approximations and modifications in sheath parameters are needed. Until now, there have been no studies that have investigated the various representations of the sheath layer in the EMT modelling, and nor has there been an analysis of its effect on the accuracy of simulation results. It has been assumed that detailed sheath layer parameters are irrelevant and that they have a minor relevance when it comes to modelling, since the compound sheath layer is connected at the cable line ends and most of the current flows through the wired sheath layer. However, even smaller errors in cable data can result in issues when the length of the cable and the number of cross-bonding points increase.

Cable sheath modelling approaches are analysed and compared by basing them on their impedance characteristics (in publication [III]). It has been shown that when it comes to frequency, the most accurate response came from the impedance characteristics of the most precise cable sheath modelling approach. The least accurate results were seen in the most simplified sheath modelling approach. Nevertheless, the variations were minor. From the perspective of network operations it is necessary to evaluate the sheath layer modelling approaches when it comes to the real network, with this evaluation also including transient events. The interest of the TSOs is in determining any possible deviations in the simulation results, when the often-employed simplified modelling approach is being implemented for the time domain EMT network studies. The results which were published in [I] and Chapter 3 indicate that real network modelling for time domain EMT studies has a higher level of sensitivity when it comes to the selected sheath modelling approach. The sheath modelling approach has an impact upon simulation results across the entire network, and variations in network bus voltage values appear. The deviation in simulation results which need to be considered when simplified sheath modelling is being used can be up to 5%.

The correct sheath representation and modelling in EMT gains a level of importance not only for a wide range of network studies but also for specific cable line studies. From the network planning point of view, the current and voltage levels in the cable sheath layer become essential when deciding on the most effective cable line installation method. In publication [II] and Chapter 3, the cable line sheath current and voltage levels for both ends bonded and cross-bonded cable line installations are shown based on a real 110 kV transmission network. At the transmission network level, no such comparable analyses have so far been found in the available literature.

Another concern in network EMT modelling is determining the correct range of network area for a simulation. When analysing transmission systems, the specific part of the network is modelled in respect to the area of interest and the phenomena being studied. Modelling large network areas is time consuming and inconvenient. It is reasonable to model as small a part of the network as possible, while at the same time maintaining accuracy and analysing the total impact area. Transients in cable networks travel at various speeds which are different from those in OHL networks, and there are addition reflections and refractions in the surge wave. Therefore, the extent of the cable network modelling area is expected to be unequal across any network which is based on the use of OHLs. No studies could be found which deal with the matter of the extent of the simulation area for cable networks or networks which include several cable lines. The results of this analysis are presented in publication [I] and in section 3.6. The transients in the cable network penetrate to the farther point in a network. It has been found that the modelling area for cable networks needs to be more than twice as large as that of a comparable OHL network. This is something that is related to the total proportion of cable lines in the network. The higher is the share of cable lines and the longer is their total length in a network, the higher will be the sensitivity level for transients, and in such cases a wider modelling area should be considered.

Practical Implementation

Electrical behaviour in a cable line and in a conventional OHL is significantly different and, therefore, the transition from OHL to cable line technology cannot be considered on a one-to-one basis. Various network phenomena-related studies in this thesis have demonstrated that in transmission networks which contain cable lines, implementing generalisation approaches or their equivalents by basing them on other networks will be inaccurate. Every system is different in terms of its configuration, with the proportion and length of lines varying along with the line installation methods that need to be used. Therefore, in terms of transmission network planning, as well later when analysing network phenomena, an individual approach is necessary.

The process of compiling the network model for EMT studies demands effort and can be time consuming, especially when cable lines are included to a large extent. Cable lines are recognisable by their complex structure and the additional conductive sheath layer. There can also be limitations present in the available data and computational resources. In network studies that have been conducted up until now, it has been assumed that precise sheath layer modelling is not essential. The sheath layer modelling methods that have been developed in this thesis deliver more clarity to cable sheath modelling and show that the former statement is not fully accurate.

The development and implementation of various cable sheath modelling approaches across the rather wide area of the transmission network in terms of EMT studies has indicated that the chosen sheath layer precision level has a direct impact upon the simulation results, affecting the accuracy of the results that have been or can be obtained. In terms of transient studies, the modelling of the cable sheath is a step that should be taken most carefully, since the representation of the sheath layer will have a greater impact for high frequency phenomena. It is evident that the most preferred sheath modelling approach is the one which responds in the most detail to the actual cable. However, alternative and less demanding methods in terms of effort can be implemented as well if certain deviation rates in simulation results are taken into account.

Cable sheath studies have so far remained largely in the background. Although in transient situations, the cable sheath layer has a notable function, and with the changes taking place in transmission networks and the transition in line technology indicate that cable sheath studies have importance. The discussion over sheath modelling show a need for more extensive analysis of transmission networks, especially when the share of cable lines is increasing. Of most concern are mixed lines, where transient surges which originate from the OHL can penetrate into the cable line. In the cable line planning process, it is becoming very important to analyse the most effective cable line installation and sheath bonding methods to be used by estimating the current and voltage values that appear in the cable sheath. A wider modelling area also has to be considered for cable networks when compiling the network model, since transients in cable networks penetrate into the farther points of that network. Suggestions and the methodology that have been provided in this thesis offer structured guidelines for TSOs that can be implemented for network and cable line planning and analysis.

Future work

There are several topics that require further discussion, study, and solutions to be found.

- The cable line sheath current and voltage measurements in a real network. Measuring sheath voltages and currents in real life is a process that is complicated in already-existent and operating cable lines. The measurements are important in cross-bonding points which, in many cases, are channelled underground. Conducting measurements is easier with cable line projects that are still undergoing the installation process. It is important to compare the real-life results with simulation results while various sheath modelling approaches are being implemented in order to be able to clarify any potential deviations.
- Analyse the sensitivity of the sheath layer parameters that are provided by the manufacturer. The nominal parameters for the cable structure often contain deviations when they are compared to the actual parameters. Even slight differences may have a noticeable impact upon simulation results. This aspect needs further investigation, and an estimation needs to be made of the optimum deviations between the nominal and real-life values and a determination of the impact rate upon the simulation results.
- Frequency scan studies in relation to urban networks. It has become clear that cable lines lower the network resonance frequency. However, there are no studies available which cover this phenomenon in urban networks which have rather short cable lines. Up until now, most studies have handled one individual long cable line. It is assumed that, with short lines, the effect is not a significant one; however, in meshed urban networks the number of cable lines is greater.
- Modelling bulky cable networks in the future and increasing the simulation speed. Due to the specific nature of modern networks, the demand is increasing for network models and simulations. It has become clear that cable networks need individual detail modelling, which requires extra effort, and simulations are time consuming, needing computers which come with high levels of computational capability. This leads to a future problem in which there is a high level of demand for cable network modelling, but there are no solutions available for efficient simulations. This is a comprehensive problem that utility companies and researchers are facing in the future. How they can improve cable network modelling by reducing the simulation run time and still hold the required levels of accuracy in the results is something that requires a much wider investigation.
- Analyse transmission lines with non-uniform configurations. In the transmission network transition process, the TSOs are faced with mixed networks and lines. Lines can have an OHL section and also a UG cable line section. Specific studies are needed to be able to investigate situations in which some parts of a cable

line have implemented different sheath bonding methods. These situations can arise in circumstances such as, for example, when the OHL part of a mixed line has been replaced by a UG cable line, but the latter line has different bonding method than the older sections of the same cable line.

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Abstract

In modern transmission networks, overhead lines (OHLs) are a traditional solution when it comes to energy transfers. However, this trend is undergoing a process of change, and more often these days it is underground (UG) cable lines that are being seen as a sustainable solution. An example of this can be drawn from several countries where there is an intention to replace conventional OHLs with UG cable lines. In future transmission networks UG cable lines are seen as being dominant. Thanks to this trend, electrical systems are becoming more complex, with several new technologies being employed alongside cable lines and conventional network operational characteristics being changed. This leads to a higher demand for network modelling and extensive transient phenomena analysis in the planning process. This thesis discusses modelling for HVAC cable lines and an assessment from the transmission network planning perspective.

Modelling cable lines with the EMT-based software is more complicated than is OHL modelling, due to the cable layered structure. Up until now, none of the available studies have highlighted cable sheath modelling principals and several approximations have been used, one which exclude the cable sheath either partially or entirely. In this thesis, sheath modelling approaches are developed by basing them on the precision of the sheath layer's representation and its response to the actual cable structure. Contrary to what has been understood in the past, the simulation results for a real-life network indicate how cable sheath modelling can have a direct impact upon simulation results. The correct representation of the sheath layer becomes significant in high frequency transient studies, since transient currents and voltages travel through the sheath layer. This thesis provides recommendations for deciding upon a fully-sufficient sheath modelling method.

The correct cable sheath representation in terms of modelling has a level of importance when it comes to analysing network operations. In the case of mixed lines, those which containing OHLs and a cable line, it is important to address overvoltages that can originate from OHL transient events and will penetrate into the cable line sheath layer. If a cross-bonded cable installation is implemented, any overvoltage at the cross-bonding point can be significantly higher than it is at the line terminals. This type of cable line installation becomes increasingly prone to failure. In order to ensure the safety and effectiveness of the cable line, the correct installation and sheath bonding method needs to be analysed in the planning process. If cross-bonded cable installation is chosen, then the optimum number of cross-bonding points need to be defined. Therefore, it becomes essential to analyse cable line operations and assess current and voltage levels in the sheath layer. This thesis analyses cable line operations in the example of a real-life transmission network, focusing on the current and voltage levels that are present in the sheath layer. The mixed line configuration is observed with two different cable line installations, one which has a both ends bonded sheath layer and one which has a cross-bonded sheath layer. The results make it possible to estimate the need to limit sheath current and voltage and helps when it comes to deciding about the cable line installation method at the planning stage.

Due to the increasing share of cable lines in transmission networks, it is becoming ever more essential to determine the sufficient network area for modelling. Previous work indicates that events which occur on the OHLs can penetrate into the cable lines. The surge wave's travelling speed is different between the two line technologies. In addition, there are reflections and magnifications in the surge wave at the line transition point and in the cross-bonding points of the cable line. This thesis deals with conducting an analysis of transient dispersion in the transmission network in relation to cable lines and OHLs. With the increasing share of cable lines, the network modelling area needs a reassessment of the previous understanding of the extent of a sufficient network modelling area. In cable networks, any transient phenomena is more far-reaching in the transmission network.

The results of thesis have practical value in terms of transmission system planning. It helps to assess the effects on the transmission system which may be related to cable line installations, and provides recommendations for modelling HVAC cable networks. Specific suggestions are also made for modelling cable lines, and in terms of assessing and deciding about their installation methods at the network planning stage.

Keywords
Cable lines, Cable modelling, Cable sheath bonding, Cable sheath modelling, Circulating sheath current, Cross-bonding, Electromagnetic transient phenomena, Induced sheath voltage, Mixed lines, Mixed networks, Network modelling area, Network studies, Sheath impedance characteristics, XLPE cables

Lühikokkuvõte

Ülekandevõrkudes on tavapärane elektrienergia edastamine õhuliinide vahendusel. See trend on aga muutumas ning aina enam nähakse jätkusuutlikuna maakaabelliinide rajamist. Nii mõnedki ülekandevõrgu operaatorid on seadnud eesmärgiks õhuliinide järk-järgulise asendamise kaabelliinidega. Nende tegevus on eeskujuks ka teistele ning tulevikus võib oodata kaabelliide domineerimist õhuliinide üle. Nii sellest kui ka mitmete uudsete tehnoloogiate kasutuselevõtust tulenevalt muutuvad elektrivõrgud üha komplitseeritumateks ning muutuvad võrgu senised tavapärased karakteristikud. Seega suureneb vajadus ülekandevõrgude modelleerimiseks ja erinevate siirdeprotsesside laiaulatuslikuks analüüsimiseks, ennekõike võrgu planeerimise ja analüüsimise seisukohast. Käesolev töö vaatlebki kõrgepingeliste kaabelliinide modelleerimist ja analüüsi ülekandevõrgu planeerimise seisukohast.

Kaabelvõrkude modelleerimine elektromagnetilisi siirdeprotsesse käsitlevate programmidega on tunduvalt keerulisem kui õhuliinide modelleerimine – seda eelkõige nende keerulise ehituse tõttu. Senini avaldatud töödes pole rõhku pandud kaabli ekraanikihi modelleerimise põhimõtetele ega sellele, kuidas kaabli mudeli koostamisel rakendatud lihtsustused võiksid mõjutada simulatsioonide tulemusi. Doktoritöös on käsitletud kaabli ekraanikihi erinevaid lihtsustuse meetodeid, lähtudes ekraani parameetrite detailsusest ja selle vastavusest kaabli tegelikule ehitusele. Senimaani eeldatu, et ekraanikihi detailsus ei avalda olulist mõju simulatsiooni tulemusetel, lükatakse käesoleva töö tulemustele tuginedes ümber. Selgub, et kaabli ekraanikihi modelleerimise meetodi valik avaldab otsest mõju simulatsioonitulemuste täpsusele. Korrektne ekraanikihi modelleerimine on oluline just kõrgsageduslike siirdeprotsesside uurimisel, kus ekraani üheks ülesandeks on rikkevoolude ja liigpingete juhtmine. Töös on esitatud soovitusi ekraani modelleerimise meetodi valikuks.

Kaabelliini korrektne mudel ja ekraanikihi arvestamine mängib rolli elektrivõrgu talitluse analüüsimisel. Segaliinide puhul, mis koonevad õhuliinist ja kaabelliinist, tuleb silmas pidada, et õhuliini rikete korral kanduvad märkimisväärsed liigpinged kaabelliini ekraanikihti. Kui rakendatakse ekraanikihi ristühendamist, siis võib ristühenduspunktides tekkiv liigpinge osutuda oluliselt kõrgemaks kui seda on liini otspunktides. Sellised liinid on rikkealtimad. Ohutuse tagamiseks aga ka liini talitluse efektiivsuse seisukohast on liini planeerimisel tarvis valida õige liini paigaldusviis ehk ekraanikihi ühendusmeetod. Kaabelliini ekraanide ristühenduse korral tuleb valida optimaalne ristühenduspunktide arv. Selleks on liini talitlusel tarvis hinnata ekraanis tekkivate voolude ja pingete väärtusi. Töös analüüsitakse kaabelliini talitlust reaalse ülekandevõrgu näitel ning keskendutakse liini ekraanis tekkivate voolude ja pingete väärtuste analüüsimisele erinevate elektrivõrgu talitluste korral. Segaliini näitel on analüüsitud nii liini kahest otspunktist ühendatud kui ka ristühendatud ekraaniga kaabelliini paigaldusviisi. Tulemused võimaldavad hinnata ekraani pingete ja voolude piiramise vajadust aidates otsutada ühendusmeetodi valiku üle liini planeerimisel.

Kaabelliinide osakaalu suurenemisega ülekandevõrgus, on modelleerimise ja analüüside tegemise seisukohast oluline määratleda piisavalt laiaulatuslik võrgu modelleerimise (mudeli koostamise) piirkond. Liigpinged õhuliinidelt kanduvad elektrivõrgus edasi kaabelliinidesse. Liigpingelaine levimise kiirus kahe liinitehnoloogia vahel on aga erinev ning segaliinide korral tuleb õhu- ja kaabelliini ühenduspunktides (aga ka kaabelliini ristühenduspunktides) arvestada täiendavalt liigpingelaine peegelduste ja võimendustega. Doktoritöös on analüüsitud siirdeprotsesside edasikandumise ulatust õhu- ja kaabelliinidest koosnevas ülekandevõrgus. Tulemustest selgub, et kaabelliinide osakaalu suurenemisega tuleb senine arusaam võrgu modelleerimise ulatusest ümber hinnata, kuna kaabelliinide tõttu on siirdeprotsesside edasikandumine võrgus kaugeleulatuvam.

Doktoritöö tulemustel on praktiline väljund ülekandevõrgu planeerimise seisukohast – need aitavad hinnata kaabelliinidega kaasnevaid mõjusid elektrivõrgu talitlusele ning annavad soovitusi kaabelvõrkude mudelite koostamiseks. Esitatakse konkreetseid soovitusi kaabelliinide modelleerimiseks, paigaldusmeetodite hindamiseks ja valikuks võrgu planeerimisel.

Märksõnad

Ekraani indutseeritud pinge, ekraani näivtakistuse karakteristikud, ekraanis ringlev vool, elektrivõrgu modelleerimise piirkond, elektrivõrgu uuringud, elektromagnetilised siirdeprotsessid, kaabelliinid, kaabli ekraani modelleerimine, kaabli ekraani ühendus, kaabli modelleerimine, ristühendus, segaliinid, segavõrgud, XLPE kaablid

Appendix 1 – Included Publications

Publication I

T. Kangro, J. Kilter, J. De Silva, "Comparative Analysis of HVAC Cable Metallic Sheath Modelling Approaches for Network Studies," *IEEE 18th International Conference on Harmonics and Quality of Power (ICHQP18)*, Ljubljana, Slovenia, May 2018.

Comparative Analysis of HVAC Cable Metallic Sheath Modelling Approaches for Network Studies

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Abstract— **This paper discusses high voltage ac underground cable sheath layer modelling for network studies in EMT type program. In EMT studies, the cable compound sheath layer is considered as a single solid layer, therefore the simplified sheath layer representation is needed. This paper presents developed approaches for cable sheath modelling. The approximations made in sheath parameters can lead to inaccuracies in study results. Therefore to determinate the sheath modelling accuracy, network power flow, short-circuit and lightning surge studies are analyzed. The network bus voltages are observed and compared at various sheath modelling approaches. Network power flow study shows no major variation in results when different modelling approaches are used. However, the short-circuit and lightning surge study results show that chosen cable sheath modelling approach has significant effect to the network bus voltage values. The needed extent of network modelling area is also analyzed in this paper. At cable networks, the considered modelling area needs to be wider than for OHL networks. The extent of modelling area should be decided corresponding to the total length of cable lines. Cable sheath modelling approach recommendations for network studies are provided in this paper.**

Index Terms-- **EMTP, cable sheath modelling, network studies, XLPE cables.**

I. INTRODUCTION

The proportion of underground (UG) HV cables in transmission networks is rapidly increasing, especially in urban areas. When constructing new transmission lines or reconstructing already existing network, the UG cables are often favored over the traditional overhead lines (OHL). Population density, environmental effect, higher reliability and security need, etc., are reasons to prefer UG cable lines. In addition, growing share of renewable energy and expanding electricity market areas higher demand on reliable interconnections between transmission system regions, increase the construction of HV UG cables.

UG cables differ significantly from OHLs by their construction, characteristics and natural behavior in electrical networks. Networks involving cable lines need additional attention and the comprehensive studies for HV cable networks are required. Compared to the OHLs, cables have considerably greater capacitance, thus reactive power compensation might be needed. Another important aspect is that the increasing number of cable lines in transmission network lower the system natural frequency. Therefore, the resonance overvoltage studies become highly relevant and the correct cable line representation crucial to obtain accurate study results. However, the layered structure, frequency dependent parameters and the distributed nature of cable characteristics makes cable line modelling often challenging.

One of the concerns in cable modelling is the proper representation of cable metallic sheath layer. Which is often made more complicated by the lack of available sheath layer parametric data. Fig. 1 present the typical single-core XLPE insulated cable structure [1]. Metallic sheath is the first conductive layer after the core conductor in cable structure. The main function of metallic sheath is to nullify the electric field outside of the cable and provide a return path for the charging currents, as well as carry the fault currents to earth [2]. The HV cable sheath is normally designed as compound layer. Most commonly, copper or aluminum wires are longitudinally welded together with metallic tape (Al, Cu, Pb) and with semi-conductive tape between them. Thus, cable sheath is composed by two conductive elements with different resistance and thickness. However, it is common practice to model the sheath layer as a single solid layer. This is supported by the fact that wired sheath and metallic tape are connected together in cable ends and junctions.

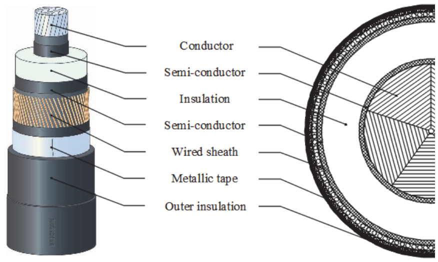

Figure 1. Single-core XLPE insulated HV cable structure.

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The cable model in EMT type software assumes the cable sheath to be single solid conductor, with equivalent thickness and resistivity. Therefore, when building cable model for EMT studies, simplifications are needed and the compound layer must be converted into solid layer [3]-[4]. It is evident that simulation results can be as accurate as are the model input parameters. Therefore, the evaluation of approximations made in cable sheath layer representation becomes essential. The more detailed the cable model responds to actual cable structure and parameters, the higher accuracy rate in simulation results will be achieved.

In literature [3]-[14], there can be found several approaches approximating sheath layer in cable model. In most cases, it is found that representing sheath resistivity with simple copper or aluminum resistivity is enough. Since most of the current in sheath layer attends to flow through wired sheath and therefore the metallic tape in cable structure can be neglected [4]-[5]. Although, in [6]-[8] it is mentioned that the air gaps between the wires and the effective cross-section area of the wired sheath should be considered. Therefore, the nominal resistivity of wires is increased. On the other hand, in [9]-[11], the cable sheath layer is considered more detail responding to the actual cable design. The cable sheath layer resistivity is corrected by including the metallic tape data.

Based on the previous studies, there is no comparative or general understanding which sheath modelling approach should be used and how this affects the network study results. Until now, cable sheath layer approximations for EMTP model are made based on the common practice or general preference. The aim of this work is to establish cable sheath modelling approaches according to the simplifications made in sheath layer and verify the effect of sheath modelling approaches to the results at various networks study cases. The comparison between various sheath modelling approaches indicate to the level of detail needed in cable model and sheath parameters for different network studies. More clarity is provided in the selection of cable sheath modelling approach.

Section II introduces developed HV ac cable sheath modelling approaches. In Section III, the study network is described and the study results at network power flow, short-circuit and lightning surge event are presented. Section IV analyzes the results and determinates suitable cable sheath modelling approach for each network study case. In section V, the conclusions are made.

II. CABLE SHEATH MODELLING APPROACHES

The commercial programs used for EMT studies consider cable sheath as solid conductive layer. The parameters that can be defined by the user are the solid layer thickness (outer diameter) and resistivity. Respectively to the approximations made in compound sheath layer parameters, various approaches are developed for cable sheath modeling in EMT type programs, according to the level of detail in cable sheath structure and parameters.

In following, developed cable sheath modelling approaches are introduced respectively to the sheath layer characteristic parameters. In each approach (Case 1, Case 2, Case 3 and Case 4), the sheath layer is modeled with different detail level, from the most simplified (Case 1) to the most complex (Case 4) approach.

A. Case 1

Case 1 is the most simplified cable sheath representation. The wired sheath layer (Fig. 1) is considered as a simple tubular solid conductor with nominal copper or aluminum resistivity. Since it is assumed that most of the sheath current is travelling through the wires [6], the metallic tape in sheath design is neglected. The sheath conductor resistivity is set to copper nominal resistivity $1.724 \cdot 10^{-8}\ \Omega \cdot \mathrm{m}$. Sheath layer outer radius, given in manufacturer datasheet represents both, the thickness of the copper wires and the metallic tape. When inserting parameters in cable model, the sheath layer outer radius should be decreased according to the neglected metallic tape thickness.

B. Case 2

Common practice for cable sheath modelling is to consider the sheath resistivity equal to the wired sheath resistivity doubled [6], [8]. The sheath resistivity is increased to take into account sheath layer effective cross-section are and air gaps between the wires. Case 2 represents modelling approach, where cable sheath resistivity is taken doubled copper resistivity $3.448 \cdot 10^{-8}\ \Omega \cdot \mathrm{m}$. The outer radius of the sheath is treated in the same manner as in previous Case 1.

C. Case 3

Case 3 represents more improved cable sheath modelling approach. Similarly to the previous two cases, Case 3 also represents only wired sheath layer in cable design. However, the improvement has been made by correcting the sheath resistivity value by (1) according to the real cross-section area of the wired sheath layer (1). The A_s represents the conductor's cross-sectional area, r_2 and r_3 are sheath inner and outer radiuses, respectively [9].

$$\rho_{Cu}^{'} = \rho_{Cu} \frac{\pi\left(r_2^2 - r_3^2\right)}{A_s} \tag{1}$$

Sheath geometry is treated in the same manner as in Case 1 and Case 2, where sheath layer outer radius given by manufacture is decreased according to the neglected metallic tape thickness.

D. Case 4

Case 4 approach represents cable sheath layer in most detail by responding to the actual cable design and including the metallic tape (Fig. 1). To consider sheath full design in EMTP cable model, an additional calculation is needed. The previous correction made in sheath resistivity by (1) is improved as shown in (2), where the A_{Cu} is the area of copper wires and A_{Al} the metallic tape (aluminum foil) area [10].

$$\rho_s^{'} = \rho_{Cu}^{'} \frac{A_{Cu}}{A_{Cu} + A_{Al}} + \rho_{Al} \frac{A_{Al}}{A_{Cu} + A_{Al}} \tag{2}$$

The sheath outer radius in Case 4 approach includes both, the wired sheath and metallic tape thickness. To implement Case 4 approach in cable model, the detailed cable sheath parameters from manufacturer are needed.

E. *PI-section*

In addition to the introduced cable modelling approaches, an extra simulation case has been included, where cable lines in study network are modeled as commonly known simple PI-sections. Modelling with PI-sections provides correct impedance only at fundamental frequencies [12]. Therefore it is not accurate method for other than modelling at fundamental frequencies and it is primarily used for steady-state studies. In PI-section, the cable parameters are represented as R, L and C elements and cable layered structure is excluded entirely. It is evident that in wide range network studies, modelling cables as PI-sections is the most simplified and indirect approach.

III. NETWORK STUDY AND RESULTS

The analyzed 115 kV transmission network is presented in Fig. 2. The study network is characterized with relatively short, only up to 8 km transmission lines. Also both, the OHLs and cable lines are included, with the respective proportion 70% and 30%. The study area includes 18 network buses and the distant transmission network area is modeled as system equivalent (EQ) in network model borderlines. The study network represents a part of a typical meshed urban network. The study network is modeled in PSCAD and also verified by corresponding network PSS/E model.

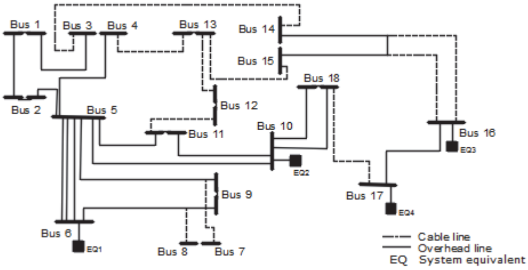

Figure 2. The 115 kV transmission network area under the study.

The developed cable sheath modelling approaches are analyzed at network various operational conditions, such as nominal power flow, short-circuit and high frequency lightning studies. Different cable sheath modelling approaches (Case 1, Case 2, Case 3, Case 4 and PI-model) are compared and their effect analyzed base on the observed variations in network bus voltage values. The bus voltages demonstrate most straightforward the sheath modelling approach effect to network study results. The variation in study results indicate the implemented cable sheath approach accuracy.

In following, the study result for network power flow, short-circuit and lightning conditions are examined by considering all cable sheath modelling approaches introduced in section II.

A. *Power Flow Study*

First, the network power flow is studied. Fig. 3 present the study results, where various cable sheath modelling approaches (Case 1, Case 2, Case 3 and Case 4) are used. The voltage RMS values on network buses are compared with the most precise Case 4 modelling approach, which is considered as a reference case. In Fig. 3 the network bus voltage variations are presented as percentage values. The buses with the highest voltage variations and buses close to cable lines are pointed out. For network PSCAD model verification and comparison, the PI- model approach and network PSS/E model power flow study results are include.

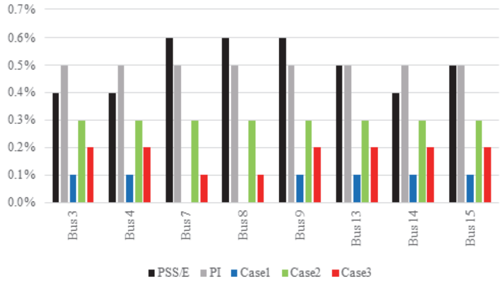

Figure 3. Cable sheath modelling effect to network bus voltages at power flow study.

It can be seen that the greatest variation in bus voltage values appears between the most detailed cable sheath modelling approach Case 4 and the most simplified PI-model. With PI-model implementation, the bus voltage values may vary up to 0.5% from the Case 4 results. The least difference in network bus voltages can be noticed between cable sheath modelling approaches Case 4 and Case 1.

From network power flow study results, it can be seen that the EMTP cable PI-model and PSS/E model results are in close agreement. The difference in bus voltage magnitudes between EMTP PI-model and PSS/E model results is not more than 0.1%. These close results ensure the validity of composed study network PSCAD model.

B. *Short-Circuit Study*

It is essential to also include transient behavior when analyzing cable sheath modelling effect to network study results. Since at transient phenomena most of the fault current is carried by cable sheath layer, it is expected to have a considerable impact to the simulation results. In short-circuit study, the three phase to ground fault is applied on network Bus 13 (Fig. 2). Bus 13 is connected to the network through cable lines, therefore cable sheath modelling effect becomes most visible. Bus voltage RMS variations between different sheath modelling approaches during the fault incident can be seen in Fig. 4. The study results are similarly to the previous power flow study presented as percentage values from the reference Case 4 modelling approach.

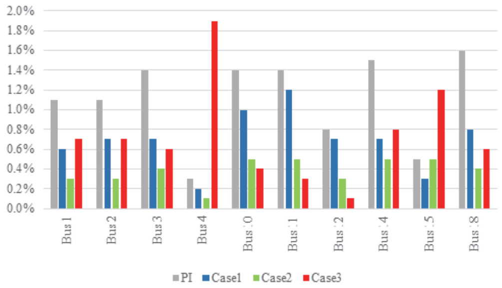

Figure 4. Cable sheath modelling effect to network bus voltages at short-circuit study.

The results in Fig. 4 show that in case of fault situation, the cable sheath modelling approach has noticeable impact to network voltage values. The highest voltage variation appears between Case 4 and PI-model, where the utmost voltage variation reaches up to 1.6%. Although, the greatest variation 1.9% can be seen on Bus 4 between the Case 4 and Case 3. However, analyzing all network buses, Case 3 results are in general lower than the PI-model results. Since Bus 4 is directly through cable line connected to the fault location Bus 13 (Fig.2), the higher variation indicates that Case 3 modelling approach is more sensitive to the fault location in network. On the other hand, closest simulation results in case of fault situation are achieved between the Case 4 and Case 2 approaches.

C. *Lightning Study*

In following, the cable sheath modelling approach effect is analyzed at high frequency transient phenomenon. A lightning study is performed with a surge waveform 1.2/50 µs on Bus 13 (Fig. 2) in network. Similarly, to the previous studies, the variations in bus RMS voltage values are observed during the lightning occurrence. Table I represent percentage voltage variations compared to the reference Case 4 approach results for all network buses. The buses are marked with colors respectively to the distance level from lightning surge location on Bus 13 (Fig 2).

The lightning study results in Table I show that at high frequencies, cable sheath correct presentation has significant impact to the study results. The utmost 16.7% variation in bus voltage values is observed between the most detailed Case 4 and the simplest PI-model approach. Additionally, it can be seen that when implementing PI-model, the higher voltage variation is obtained on network buses which are more distance from the lightning occurrence, such as Bus 7 and Bus 8. Therefore, cable lines closer to the network transient phenomenon are more sensitive to the correct cable sheath modelling approach. Study results presented in Table I confirm that at high frequency studies, the cable line PI-model representation becomes inaccurate. The magnitude level of voltage variation for other approaches (Case 3, Case 2 and Case 1) is significantly lower, being 4.7% between Case 4 and Case 3 and 3.2% between Case 4 and Case 2. For Case 1, the voltage variation stays below 0.6%. According to study results in Table I, at lightning study the closest results in network bus voltages are achieved between cable sheath Case 4 and Case 1 approaches.

TABLE I. VOLTAGE VARIATIONS AT LIGHTNING STUDY

Network bus	**Voltage variation compared with Case 4 (%)**			
	Case 1	***Case 2***	***Case 3***	***PI-model***
Bus 1	0.60	0.30	0.10	9.70
Bus 2	0.50	0.50	0.20	6.20
Bus 3	0.40	1.30	3.00	8.70
Bus 4	0.50	1.40	1.30	0.80
Bus 5	0.20	1.10	0.10	1.30
Bus 6	0.20	0.50	0.10	6.30
Bus 7	0.30	0.20	0.40	16.00
Bus 8	0.30	0.20	0.40	16.70
Bus 9	0.30	0	0.10	10.60
Bus 10	0.40	1.80	0.20	14.50
Bus 11	0.10	3.20	3.50	1.40
Bus 12	0.20	3.00	4.20	1.90
Bus 13	0.10	2.70	4.70	0.80
Bus 14	0.40	1.00	3.30	3.90
Bus 15	0.50	2.60	2.40	1.10
Bus 16	0.30	0.20	0.10	2.60
Bus 17	0.20	2.10	1.00	0.30
Bus 18	0.10	1.70	2.20	0.80

IV. DISCUSSION

Performed network study results show that detail cable sheath representation can become highly relevant, especially at EMT studies. The network power flow study results showed no noticeable difference whether cable sheath is modeled as a simple solid copper layer (Case 1) or as complex two conductive component layer (Case 4). The variations in network bus voltages were rather minor. Therefore, it can be stated that for simple network power flow studies, the detailed cable sheath representation is not needed. Considering cable sheath resistivity as simply main conductor nominal resistivity, is accurate enough.

For the network short-circuit event, the correct cable sheath representation becomes more relevant. The variations in network voltage values are higher between various cable sheath modelling approaches. Cable sheath modelling Case 4 approach is considered as the reference, where sheath layer model responds most closely to the real cable design. Both conductive sheath layers are included with their characteristic parameters, the wired sheath and metallic tape. In often cases, the availability of sheath detailed parameters is limited. Therefore, approximations made in sheath data are needed for EMT studies.

Short-circuit study results indicate that closest results with the most detail Case 4 approach are achieve when alternative Case 2 approach is implemented in cable model. Case 2 approach represents cable sheath as simple solid layer with wired layer material nominal resistivity doubled. The utmost voltage variation on network buses between Case 4 and Case 2 reaches up to 0.5%. Short-circuit study results confirm that most inaccurate results are achieved when implementing simple PI-model for cable modelling.

The high frequency lightning occasion study results (Table I) also confirm that correct cable sheath representation in cable model has significant impact to the study results. The variations in network bus voltages are higher compared to the short-circuit study results. The closest results to the most accurate sheath modelling Case 4 approach are achieved when the Case 1 approach is used, with the maximum observed voltage variation 0,6% (Table I). Therefore in case of network lightning studies, where detail cable sheath data is unavailable and precis sheath modelling becomes impossible, the simplest sheath modelling Case 1 approach should be preferred amongst other modelling approaches.

Case 1 approach considers sheath layer as solid layer with the nominal resistivity of wire material. From the study results it appears that intermediate parametric modifications made in cable sheath, such as taking into account the spaces between wired sheath and increasing the resistivity accordingly, can lead to incorrect study results. As expected, the lightning study results also confirm that most inaccurate cable sheath modelling approach is PI-model, where cable sheath layer is completely excluded. Since PI-model is applicable only at fundamental frequencies, it becomes irrelevant at high frequency transient studies.

It is important to evaluate obtained results in real network operational perspective and determinate the possible consequences when inadequate cable sheath modelling approach is chosen for network studies. Therefore in Fig. 5, the lightning study results are presented as per unit voltage values. Hereafter cable PI-model representation is excluded, since it is proven to be unsuitable for cable network studies.

At network lightning occasion, the highest 4.7% voltage variation appears between Case 4 and Case 3 (Table I). In Fig. 5, the respective voltage magnitudes are 1.04 pu and 1.09 pu. The difference is only 0.05 pu, which can be considered as a simulation error. For example, the allowable steady-state voltage variation in 110-300 kV networks is according to [16] 0.9-1.118 pu. Therefore, when cable sheath approximations are used for network studies, the possible additional 5% deviation in network voltage values should be taken into account. However, when specific network studies are performed, especially for control systems for example, the 5% deviation can obtain great importance. When a certain cable line is under the study or high frequency studies are performed, the most detailed cable sheath modeling approach should be considered.

The lightning study results in Table I and in Fig. 5 demonstrate the sensitivity of the chosen cable modelling approach to the high frequency transient event location. The lightning surge waveform has a damping nature in the network. Correctly chosen cable sheath modelling approach becomes more relevant in the network points closer to the lightning occurrence. Analyzing the sensitivity of different modelling approaches (Fig. 5), it can be noticed that Case 3 results shows no correlation with the lightning occurrence distance. While other sheath modelling approaches (Case 1, Case 2 and Case 4) show relevance of cable lines closer to the lightning surge occurrence.

To assess the extent of network modelling area, the voltage levels at power flow and lightning study are compared in Fig. 6. Network Bus 13, where the lightning surge event is applied, is connected with neighboring buses (first level) only through cable lines. In Fig. 6, it can be seen that all first level buses (Bus 4, Bus 12, Bus 14 and Bus 15; yellow in Table I) are sensitive to the lightning surge event. When moving more distant in network, the voltage values on second level buses (Bus 3, Bus 5, Bus 11, and Bus 16; light yellow in Table I) show that Bus 11 is sensitive to the lightning occurrence, while Bus 5 and Bus 16 are rather not.

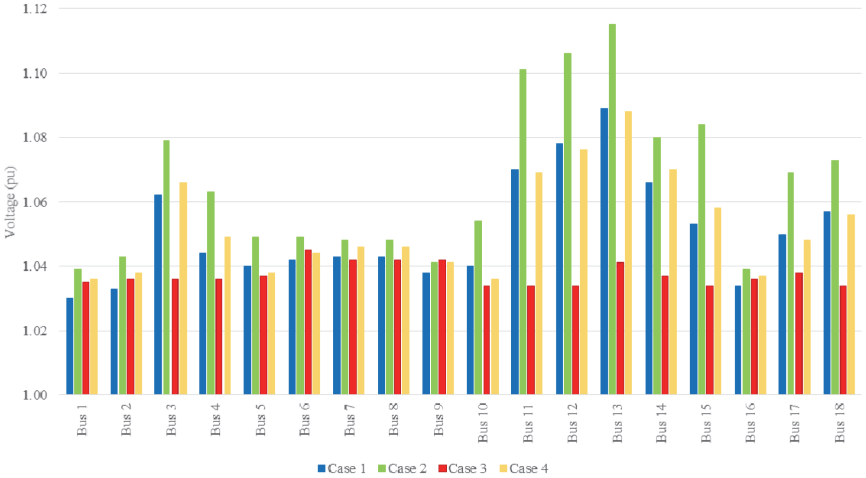

Figure 5. Cable sheath modelling effect to network bus voltages at lightning study.

This is due to the fact that latter buses are connected through OHLs, while Bus 11 is connected through cable line. Third level buses (Bus 1, Bus 2, Bus 6, Bus 10 and Bus 17; light green in Table I) are all connected through the OHLs. The voltage level on Bus 17 shows some sensitivity, while for others there is no significant effect. To analyze cable line connection in farther point of the study network, the Bus 7, Bus 8 and Bus 18 are observed (Fig. 2). Mentioned buses are all fourth level buses from the lightning surge event on Bus 13. It can be seen that for Bus 7 and Bus 8, the lightning waveform distribution has no significant effect to the voltage level, while on Bus 18 the voltage rise is noticeable. The average distances from the lightning occurrence are 16.7 km and 18.3 km, respectively to Bus 8 and Bus 18. The length of cable lines for Bus 8 is 5.3 km and for Bus it is 18 8.3 km. This indicates, that modelling area sensitivity is not only depending on the number of cable lines, but also on the total length of cable lines. The higher is the share of cable lines and the longer is their total length in network, the higher is the sensitivity and the wider modelling area should be considered. The determination on the extent of modelling area should be made based on the total length of cable lines in the network area.

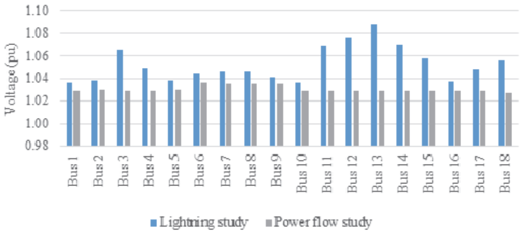

Figure 6. Network bus voltages (Case 4) at lightning and power flow study.

V. CONCLUSION

This paper takes close look at the UG cable sheath layer modelling for EMT studies. Four different cable sheath modelling approaches were developed (Case 1, Case 2, Case 3, Case 4) to determinate the effect of cable sheath approximations for network studies and verify the needed level of accuracy in cable sheath representation.

For network power flow studies, the detailed cable sheath representation is not essential. However, when the transient phenomena are studied, the approximations in cable sheath parameters become more relevant, especially in high frequency studies. It is assumed that most detailed cable sheath modelling Case 4 approach gives most accurate study results. On the other hand, when detailed cable sheath data is unavailable, the results sufficient enough can be achieved by approximating sheath layer parameters. The alternative accurate enough cable sheath modelling approach for short-circuit studies is Case 2 and for lightning studies Case 1. The final selection in sheath representation in cable model should be made based on the available data, the nature of performed study and the required accuracy level for simulation results.

The evaluation of network modelling area extent showed that cable lines have higher sensitivity to the transient phenomena event location in network compared to OHLs. For network buses connected through cable lines the transient event effect was noticeable in bus voltage values even for fourth level buses. The higher is the share of cable lines and the longer is their total length in network, the wider modelling area should be considered for EMT studies.

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Publication II

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Analysis of Transmission Network Short Cable Line Sheath Bonding Methods

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Abstract—**This paper presents the results of the study made in order to assess and clarify the selection principles of cable line sheath bonding method for short transmission network cable line. In this paper, two most commonly implemented approach, e.g. both ends bonded and cross-bonded, are discussed. Comparison between the bonding method is based on permitted sheath circulating current and induced voltage levels. Results from network load flow, fault and lightning analysis are presented. In addition, the effect of various number of cross-bonding points along the cable is shown. Results of this paper are important for transmission network planners.**

Index Terms—**cables; cable sheath; circulating current; induced voltage; system studies.**

I. INTRODUCTION

In modern transmission networks, especially in city areas, the number of cable lines is increasing. This is due to increased population density, environmental and political matters, higher reliability requirements and security concerns [1]-[2]. Several transmission system operators (TSO) have adopted regulations to replace conventional overhead lines (OHL) with UG cable lines [3]-[7].

In cable networks there are several concerns which are not present in only OHL based networks [2]. For example, the voltages and currents travelling in cable sheath layer are of importance. Overvoltage in sheath layer is a safety hazard and may lead to insulation failures. Therefore, cable system sheaths are commonly grounded either at one or at both cable line terminals (ends) [8]. Remarkable circulating currents in cable sheath lead to steady state losses and reduces cable line efficiency. It also shortens cable lifetime and can lead to faults due to insulation or jacket breakdown, as well as enhance the danger during cable line maintenance [9]. Therefore, it is essential to keep circulating current and induced voltage in cable sheath as minimum as possible. Several well-known configurations in cable line installation with various sheath grounding methods can be used [10].

The decision over the most effective method, considering the operational aspects and investment costs, is not easily defined [8]. It is evident that from induced voltage perspective, the objective is to reduce sheath voltage to a safe level. However, when method used for that results in higher circulating currents and the losses in the system are increased, a more specific analyze is needed. It can become challenging to find optimal solution where both, sheath circulating currents and voltages stay in satisfying level. Therefore, cable installation method cannot be generally predefined and it becomes relevant to assess the level of sheath currents and voltages for each cable line arrangement.

There is no uniform understanding over the allowed sheath voltage limits in cable lines. Formerly, the sheath damages and corrosion was a problem because cable sheath was in direct contact with the surrounding environment. The limit to sheath voltage was set in the range of 12 to 17 V [10]. This is currently no more of a concern as the cables are protected by insulating jacket and higher sheath voltage values can be allowed. The practice for sheath voltage level varies among countries and utilities, where the limits can be between 35 V to 400 V [11]. In many countries there are no fixed limits but depending on the utility certain limits are followed. Some current practices for sheath voltage limits applied in countries are pointed out in [10]. For example, in Great Britain the commonly used sheath voltage limit is 65 V. While in Norway 60 V is used and in Italy, typically 25 V fixed value is followed. In USA, most of the long cable lines are designed with maximum allowed sheath voltage 100 to 200 V during nominal operation. In Canada, for some instances, the maximum sheath voltage can reach up to 600 V.

The discussion over different cable sheath bonding and grounding methods can be found in [10]-[13]. There are also few studies [6], [8] analyzing sheath currents and voltages in medium voltage cable lines. In practice each installation should be studied individually, especially when cross-bonded cable installation is involved. Each case has its complexity and generalizations over study areas can lead to incorrect conclusions. This paper presents study results for sheath currents and voltages along HV cable line characteristic to Estonian transmission system in city area. The aim is to analyze sheath current and voltage levels and determinate potential limits for cable line installation. Study results help to make decisions over cable installation methods. In addition, when cross-bonded cable installation is preferred, the number of cross-bonding points is studied.

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The results presented, hold an importance for future HV UG cable network planning. The cost-effectiveness of cable installation should be critically considered and it becomes essential in terms of circuit losses and line profitability. The decision over higher transmission capacity and lower priced cable installation design, with permanent voltage rise in cable sheath, is vital.

This paper compares the both ends bonded and cross-bonded cable installation effect to sheath current and voltage values. In section II, the cable sheath grounding methods are introduced. Section III gives and overview over transmission line under study. Results are presented in section IV and discussed in section V. Conclusions are given in section VI.

II. CABLE SHEATH GROUNDING METHODS

This paper studies only two of the most common cable sheath bonding methods, bonding in both ends and cross-bonding method (Fig. 1).

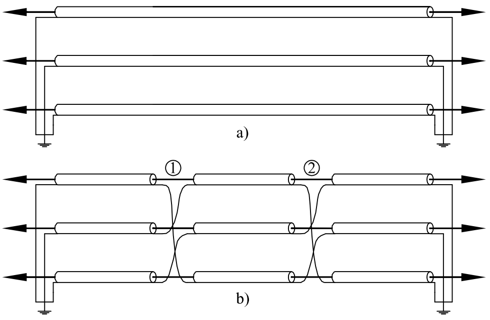

Fig. 1. Cable sheath bonding methods: a) both ends bonded and b) cross-bonded cable line.

For both ends bonded cable installation, the cable sheath is bonded and grounded in cable line terminals (sending (SE) and receiving end (RE)). It is mostly used for short cable lines, where induced sheath voltage is reduced to minimum value. As a drawback, the groundings in cable line terminals creates additional circuit for current to flow resulting to additional losses.

To reduce the sheath circulating current and losses in cable line, special cross-bonding method is used. Additionally to bonding in cable terminals, the sheath circuit is interrupted by cross-bonding points dividing cable line into sections and cable sheaths are transposed. The total induced voltage in three consecutive sheath section is therefore balanced and sheath circulating current is minimized. However, the disadvantage is the voltage rise in cable sheath. To prevent high sheath voltage values, additional groundings can be implemented in cross-bonding points. In addition, cross-bonding points are the most prone parts in cable installation. Failures result in significant sheath currents and losses leading to cable overheating [10]. Cross-bonding method can be more found in long cable line installations to reduce sheath currents and suppress induced voltages at the same time.

III. TRANSMISSION LINE UNDER STUDY

In this paper a part of Estonian 110 kV transmission network is considered. In Estonian network, both ends bonded, as well as cross-bonded cable installations are used. Objective for the TSO is to hold induced voltage level under 100 V limit. However, there is no fixed regulation nor previous analyzes for cable sheath currents and voltages.

Cable line under study is part of mixed line (Fig. 2). The proportion of OHL and UG cable is respectively 3.2 km and 3.7 km. With mixed lines there are some difficulties that do not exist in full cable networks. For example, the voltage rise due to OHL faults and the transient potential rise due to switching or lightning impulse [11]. In [14], it is stated that the worst overvoltage in cable sheath results from shielding failures or backflashovers happening on OHL close to cable line connection, where steep waveform generated by fault on OHL propagates towards the cable connection point.

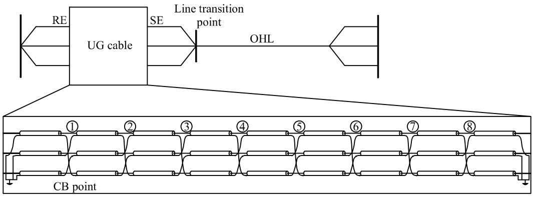

Fig. 2. Principle scheme of 110 kV mixed OHL/cable line under study.

Cable line has three single-core AXALJ-CL 1x1600 cables placed in trefoil, with installation depth of 3.8 m. Cable line installation methods are modelled in PSCAD, with frequency dependent phase model. For both ends bonded installation, the sheaths are grounded in cable terminals with resistivity 1 Ω. For cross-bonded cable installation, the cable line is divided into 9 cross-bonding sections (8 cross-bonding points), with the lengths in the range of 0.3 to 0.4 km. There are no additional groundings applied in cross-bonding points. This installation responds to the actual line in the study network. The cable line loading is considered as 95% of the maximum current carrying capacity.

IV. STUDY RESULTS

The cable line sheath current and voltage levels need to be analyzed at network load flow, as well as transient phenomena. According to [10], the sheath to ground voltage in cross-bonded cable sheath can reach to 20% of the magnitude of incoming surge. Across the cross-bonding point insulators this voltage can even be up to 40%. Therefore, it is not enough to study overvoltage levels only in cable line terminals. In reality, the overvoltage can be higher along the cable run, due to the wave reflections in cross-bonding points [14].

In this paper, the network load flow, fault situation in cable line receiving end (RE) and lightning surge occasion on nearby OHL are studied (Table 1). These studies can be considered the most relevant for this type of mixed line. The direct fault in UG cable line is rare, since cable is not exposed to external impact. More likely, the fault event may take place in cable line terminals, for example in substation or load connection point. Therefore, single-phase (phase *a*) to ground fault in cable line receiving end (RE) substation bus was chosen.

For cable line that is part of mixed line, the most probable fault situations are fault events appearing on OHL. There can be several OHL fault types, such as phase conductor (1-phase or 3-phase, ground connection) faults or lightning surge occasions. For OHL lightning study, the location of lightning surge becomes also essential. The lightning surge can hit either the OHL ground wire or phase conductor. According to [11], the current peak values may be significantly different in these cases. It is also said that for cross-bonded cable lines, the hit on phase conductor would be most harmful (with the 10 kV lightning current) [11]. In this paper, the most severe situation, the lightning on OHL phase conductor (phase *a*), close to cable line transition point is considered.

TABLE I. NETWORK STUDIES AND CABLE INSTALLATION

Network Studies		
Load Flow	***Fault in RE***	***Lightning on OHL***
Both ends bonded	Both ends bonded	Both ends bonded
Cross-bonded 8 CB points	Cross-bonded 8 CB points	Cross-bonded 8 CB points
Cross-bonded 5 CB points		Cross-bonded 5 CB points
Cross-bonded 2 CB points		Cross-bonded 2 CB points

A. Load Flow

Results of the load flow analysis for both ends bounded sheath installation are given in Fig. 3 and Fig. 4. Sheath currents (Fig. 3) for all three phases stay in the similar range throughout the total cable length. The maximum current value reaches up to 130 A, at cable line receiving end and the minimum sheath current value is 89 A, at the cable line sending end. Maximum sheath voltage (Fig. 4) occurs at cable line terminals, reaching up to 12 V value. At the minimum sheath voltage level, around 2.5 V, in all three phases is reached around cable line midpoint.

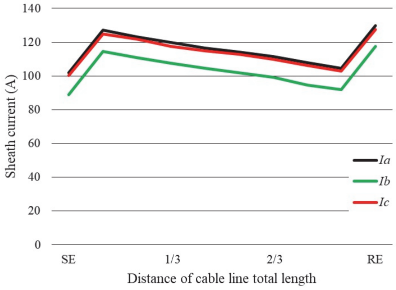

Fig. 3. Sheath currents for three-phase cable line system with both ends bonded sheath installation at network load flow.

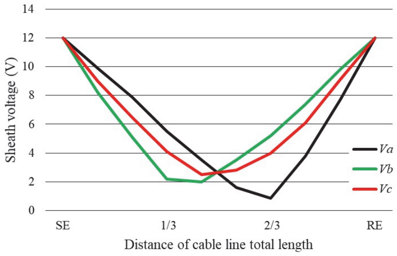

Fig. 4. Sheath voltages for three-phase cable line system with both ends bonded sheath installation at network load flow.

Fig. 5 and Fig. 6 presents the results for cable installation with sheath cross-bonding. Implementing cross-bonding reduces sheath circulating current level significantly, with the maximum value 8.5 A (Fig. 5). The lowest circulating current value is 3.2 A in phase *b* cable. Besides reducing circulating current value, cross-bonding cable sheath also balances sheath current values between all three cables throughout the cable line total length. However, in induced sheath voltage, there is no significant difference between two different cable installations. There can be noted slightly higher induced sheath voltage values in some points throughout the cable line, but it is also notable that after every three sections the sheath voltage values in all three phases are balanced and lowered.

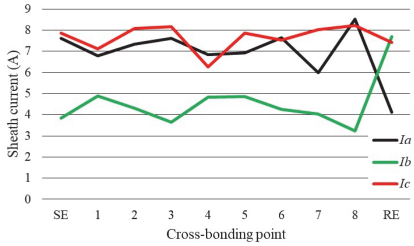

Fig 5. Sheath currents for three-phase cable line system with cross-bonded sheath installation at network load flow.

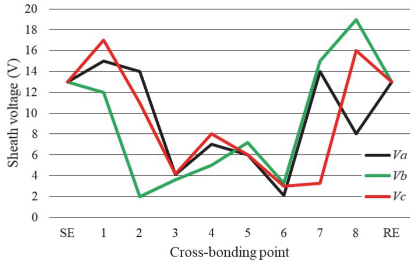

Fig. 6. Sheath voltages for three-phase cable line system with cross-bonded sheath installation at network load flow.

B. Fault in Cable Line RE

Results from single phase to ground (phase *a*) fault at the cable line receiving end (RE) in case of both end bonded option are given in Fig. 7 and Fig. 8. Cable line sheath maximum current and voltage levels are observed at the moment of fault occurrence. Single-phase fault is an asymmetrical fault, with significantly higher fault current in faulted phase than other two phases. It can be seen that cable line phase *a* sheath current, with over 7000 A value (28% of the fault current carried by cable core-conductor), is higher than the current values in other two phases, respectively over 2000 A in phase *b* and 900 A in phase *c*. Induced sheath voltage reaches up to maximum of 3 kV value at cable line terminals, and is at its minimum value at cable line midpoint. Results for sheath cross-bonding installation is given in Fig. 9 and Fig. 10. Compared to the both ends bonded option the sheath circulating currents are reduced and induced voltages has no significant differences.

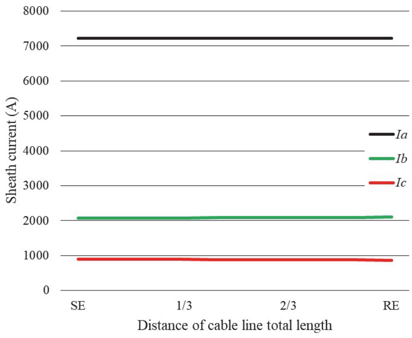

Fig. 7. Sheath currents for three-phase cable line system with both ends bonded sheath installation at fault in RE bus.

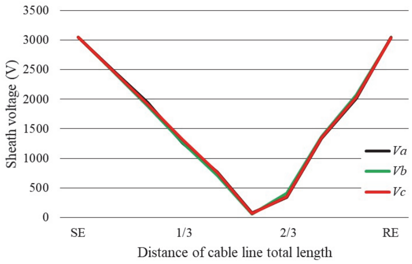

Fig. 8. Sheath voltages for three-phase cable line system with both ends bonded sheath installation at fault in RE bus.

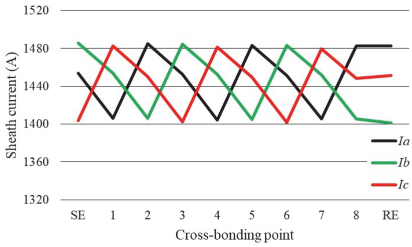

Fig. 9. Sheath currents for three-phase cable line system with cross-bonded sheath installation at fault in RE bus.

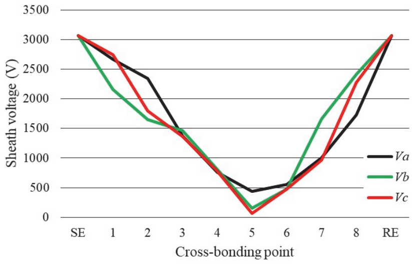

Fig. 10. Sheath voltages for three-phase cable line system with cross-bonded sheath installation at fault in RE bus.

C. *Lightning on OHL*

In following, the high frequency lightning surge occasion is studied. OHL is prone to direct lightning surges and the surge waveform can easily penetrate into cable line. For long transmission lines, the overvoltage value penetrating into cable line is not that high concern, since multiple groundings in OHL towers help to divert the current into ground [14] and transient wave damping nature along the line decreases the current magnitude value. For short lines these aspects cannot be omitted.

OHL and cable impedances are different. Depending on the impedance mismatch in the transition point, a part of transient surge travels through the cable and part of it reflects back into OHL. Therefore, the lightning overvoltage in mixed lines may become higher than the expected theoretical maximum overvoltage [15]. The surge waveform reflections in cable line remote ends and in cross-bonding points may also result in higher voltage levels inside the cable line compared to voltage in line terminals.

Results of the OHL lightning surge for both ends bonded cable installation are given in Fig. 11 and Fig. 12. The maximum sheath current during the lightning event is over 28000 A (99% of the fault current carried by cable core-conductor) (Fig 11). Maximum sheath voltage value is 19 kV at cable line sending terminal (Fig. 12).

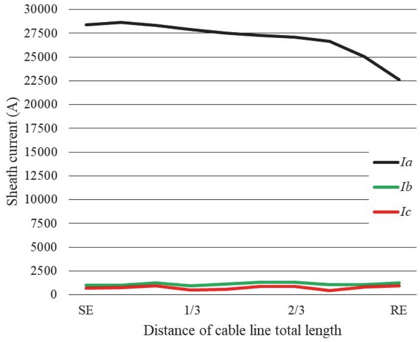

Fig. 11. Sheath currents for three-phase cable line system with both ends bonded sheath installation at OHL lightning event.

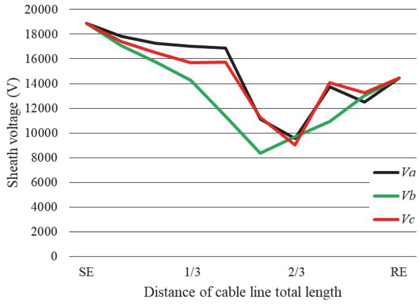

Fig. 12. Sheath voltages for three-phase cable line system with both ends bonded sheath installation at OHL lightning event.

OHL lightning study results for cross-bonded cable installation are given in Fig. 13 and Fig. 14. It can be concluded that implementing sheath cross-bonding will not help to reduce the maximum of circulating sheath currents but the currents are more balanced. This however results to higher sheath current values in phase *b* and phase *c* cable sheath, compared to both ends bonded cable installation (Fig. 11). For sheath induced voltages differences are seen. The sheath voltage in cable line sending and receiving end is in the same range with both ends bonded cable installation but, the maximum sheath voltage reaches up to 120 kV value.

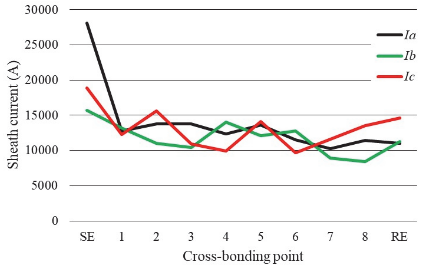

Fig. 13. Sheath currents for three-phase cable line system with cross-bonded sheath installation at OHL lightning event.

Fig. 14. Sheath voltages for three-phase cable line system with cross-bonded sheath installation at OHL lightning event.

D. *Number of Cross-Bonding Points*

Cross-bonded cable installation must have sufficient argument from technical, as well as cost-effective point of view. Higher number of cross-bonding points results in higher cable line investment costs. Therefore, the number over cross-bonding points must be decided reasonably, especially for short cable lines.

The length of cable line under the study is only 3.67 km. However, the line is divided into 9 cross-bonding sections with 8 cross-bonding points. The length of cross-bonding sections is between 0.3 m to 0.4 m. There are no additional groundings implemented in cross-bonding points along the line. In following, the effect of number of cross-bonding points to sheath current and voltage values is observed. Therefore, cable line is considered with various number of cross-bonding points, respectively 8, 5 and 2 (9, 6 and 3 cross-bonding sections). For 5 cross-bonding points, the average length for each sections is 0.62 km and for 2 cross-bonding points it is 1.22 km.

For this case network load flow and OHL lightning event are studied. At network load flow, the results for cable installation with 8, 5 and 2 cross-bonding points are presented in Fig. 15 and Fig. 16. It can be seen that reducing cross-bonding from 8 points to 5 will not result in notably higher sheath current level. However, when the number of cross-bonding points are reduced to 2, the maximum sheath current value increases 5 A. The variation in current values between all three phases along the cable length is also increased, which indicates to grater unbalance in 3-phase system. The effect on a sheath voltages is more evident (Fig. 16). When reducing cross-bonding points from 8 to 5, the sheath voltage at cable line terminals is decreasing 3 V. Along the cable line a slight increase in voltage levels can be noticed. When cross-bonding points are reduced to 2, the rise in sheath voltage level along cable line is considerable. However, the sheath voltage level in cable line terminals stays at the same level.

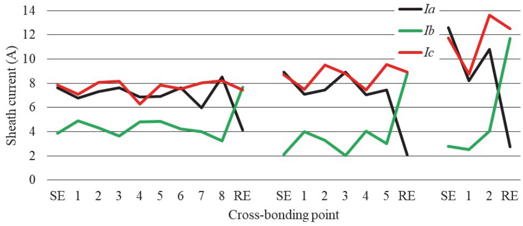

Fig. 15. Sheath currents for three-phase cable line system with 8, 5 and 2 cross-bonding points in cable installation at network load flow.

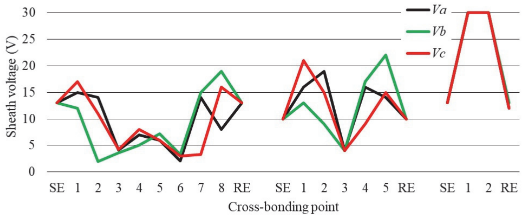

Fig. 16. Sheath voltages for three-phase cable line system with 8, 5 and 2 cross-bonding points in cable installation at network load flow.

OHL lightning study results are presented in Fig. 17 and Fig. 18. It can be seen that reducing the number of cross-bonding points in cable line will not result in significant change in sheath current level. The sheath current is in the same range for cable installation with 8, 5 and 2 cross-bonding points. There is also no significant effect when reducing cross-bonding points from 8 to 5. However, when the number of cross-bonding points is reduced to 2, the sheath voltage level in cross-bonding points is increasing by 31 kV, compared to the cable installation with 8 cross-bonding points. The number of cross-bonding points will not affect sheath voltage level in cable line terminals.

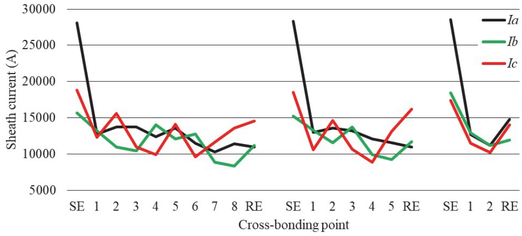

Fig. 17. Sheath currents for three-phase cable line system with 8, 5 and 2 cross-bonding points in cable installation at OHL lightning event.

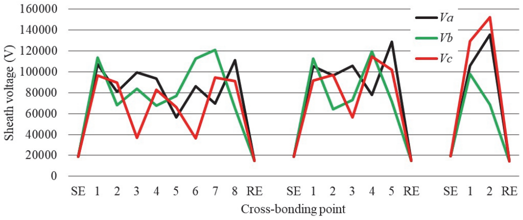

Fig. 18. Sheath voltages for three-phase cable line system with 8, 5 and 2 cross-bonding points in cable installation at OHL lightning event.

V. DISCUSSION

The comparison on both ends bonded and cross-bonded cable installation study result at network load flow show (Fig. 3 to Fig. 6) that there is significant effect to sheath circulating current values. When using cross-bonded option the sheath current value is reduced 93%, compared to the both ends bonded cable installation. Induced voltage level for both ends bonded and cross-bonded cable installation stays in the same range. At network nominal operation, the voltage level in cable sheath does not reach to a concerning level and no additional methods in cable line installation are required.

In case of single-phase fault situation in cable line receiving end (Fig. 7 to Fig. 10), remarkable current and voltage levels appears in cable sheath. With cross-bonded cable installation the sheath currents can be reduced up to 80%. The cable sheath bonding method does not have significant effect to induced sheath voltage value. To assure operational reliability and safety, the overvoltage penetrating into cable line at fault situation should be limited and corresponding sheath voltage limiters should be included in cable installation. If sheath cross-bonding method is used, the groundings in sheath cross-bonding point can be used as additional method to reduce induced sheath voltage level.

The single-phase OHL lightning study results show (Fig. 11 to Fig. 14) that implementing cross-bonded cable installation balances sheath circulating currents between all three phases. However, it will not result in reduced sheath current values. On the contrary, the circulating current value in phase *b* and phase *c* is increased. Implementing cross-bonding will also increase the sheath voltage level along the cable line in cross-bonding points. It can also be stated that for mixed lines at possible lightning occurrence, the overvoltage limiting in cable line becomes relevant, no matter which sheath bonding method in cable installation is used. Correct dimensioning of sheath voltage limiters is essential and in case of cross-bonded cable installation, the sheath voltage limiters should to be used also in cross-bonding points.

Based on the network load flow and OHL lightning study that the 8 cross-bonding point installation has not been a reasonable choice. Higher number of cross-bonding points increases investment and maintenance cost. The study results in Fig. 14 to Fig. 17 show that implementing higher number of cross-bonding points will not result in significant decrease of sheath current values. When less cross-bonding point are implemented, the cable line sheath voltage values in cross-bonding points may be increased. However, as no concerning voltage level is reached then implementing more complex cable installation is not justified.

VI. CONCLUSION

This paper compares cable line installation with two most commonly used cable sheath bonding methods, both ends bonded and cross-bonded sheath method. It can be concluded that implementing cross-bonding in short cable lines will result in significant sheath current reduction at network power flow and fault situation. However at single-phase OHL lightning situation, sheath cross-bonding will not have any improving effect to cable sheath current values. The induced voltage level in cable sheath has to be limited at fault and at OHL lightning occasions. Cross-bonding cable sheaths shows some effect to induced sheath voltage only at OHL lightning occasion, where the voltage value can be increased in cross-bonding points along the line. However, the induced voltage level in cable line terminals is not affected by sheath bonding method. Analyze over the optimal number of cross-bonding points showed that implemented 8 bonding points is excessive in this short cable lines.

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Publication III

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Assessment of HV XLPE Cable Sheath Layer Modelling Approaches for EMT Studies

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Abstract— **This paper presents the results of a study verifying the differences between various HV XLPE cable sheath modelling approaches used in EMT programs. Cable sheath is a compound layer, including two different conductive layers with a semi-conductive layer in between, but in EMT programs, it is modelled as a single solid conductive layer. In order to consider properties of the actual sheath layer, modifications in its representation are needed. For this purpose, several approaches are used but currently there is not sufficient information available to clarify what is the difference between them and how they affect simulation results. In this paper, frequency dependent sheath impedance characteristics are studied for single layer, equivalent single layer and double layer sheath approaches and simulation results are presented. It is shown that differences between various sheath modelling approaches exist and it is necessary to consider these in various system studies.**

Index Terms—**Cables, cable modelling, cable sheath, EMT, impedance characteristic, system studies.**

I. INTRODUCTION

In power system studies, it is essential to understand the characteristics of the observed system and to model its components with sufficient accuracy. This enables to perform the required studies based on which it is possible to make correct investment decisions and assess the performance of the system and its components. In current and future power systems, the share of cables is increasing and detailed knowledge on cable modelling is needed. Due to complex design and insufficient data availability from the manufacturers, the detailed modelling of cables is challenging and, for example, for cable sheath modelling there is no uniform approach available.

For electromagnetic transient (EMT) studies the cable sheath is considered as a solid single layer design. However, the actual sheath of the cable is combined layer, with two conductive layers and a semi-conductive tape between them. In EMT programs, it is possible for the user to define solid sheath layer thickness (outer radius) and layer resistivity for cable component meaning that additional calculations are needed to accurately consider and present cable sheath layer.

In the literature [1]-[15], several cable sheath modelling approximations are employed. Various approaches, for example, neglecting the outer sheath layer entirely or modifying sheath parameters according to the outer layer. In [2] and [3], the outer sheath layer is neglected and the nominal resistivity of wires is used as most of the current in the sheath layer flows through the wired sheath. In [4] and [5], it is highlighted that wire nominal resistivity should be corrected to take into account the sheath layer effective cross-section area and the free space between the wires. In [6]-[8], cable sheath responds the most to the actual sheath layer design where sheath resistivity is modified by including also the outer sheath layer.

Despite the available literature, it is difficult to obtain comprehensive clarification of the influence of cable sheath modelling methods and how the approximations made in sheath layer affect the simulation results accuracy. In [16], the comparison of cable line simulation and field measurement results have shown that representing cable sheath as a single solid conductor with specific resistance is inaccurate and reveal errors in simulation results. Due to the skin effect, the density of ac current in conductor is not uniform over the cross-section area. At higher frequencies most of the current flows in the conductor surface and cable sheath impedance becomes frequency dependent [16]. There is also lack of information on the best practice used in the industry and therefore this paper aims to provide some clarifications to this topic. It is seen essential to understand which cable sheath modelling approach should be implemented for network studies and how the results are affected by the selection.

In this paper, an assessment of different approximations for cable sheath modelling proposed in the literature is made based on variations in impedance characteristics and results of EMT simulations. In section II, an overview on various cable sheath modelling approaches and their parametric representation is provided. Section III provides discussion on cable

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sheath impedance characteristics. Section IV presents case study and results. Discussion and conclusion are made in Section V and Section VI, respectively.

II. CABLE SHEATH MODELLING APPROACHES

This paper discusses five different cable sheath modelling approaches. For cable modelling, dimensional data and material properties of all cable layers are needed. Each modelling approach in this study describes the cable sheath with a different level of detail, from the lowest to the highest level of detail, compared to the actual design of the sheath.

A. Single Layer Sheath Approach

In the single layer representation, the outer sheath layer (most commonly aluminium foil) is neglected. According to [2], this common practice is justified by the fact that most of the current travels through the wired sheath layer. There are three different sheath modelling approaches which make the approximation of including only the inner wired sheath layer. These approaches are referred to as Case 1, Case 2 and Case 3 in this study.

The most robust modelling approach (Case 1) treats the cable sheath as a solid tubular layer with its nominal resistivity (e.g. copper resistivity). Sheath thickness corresponds to the nominal value given in the datasheet of the cable. Cable layout for Case 1 is presented in Fig. 1.

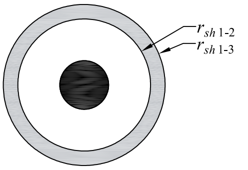


Figure 1. Cable layout and sheath layer radiuses for single layer sheath modelling approach (Case 1 and Case 2).

In reality, the actual cable sheath layer consists of wires instead of a solid tubular conductor. In order to take into account the free space between the wires, it is suggested that the nominal resistivity should be adjusted accordingly. Therefore in [2], the resistivity of the wired sheath material is doubled. In this study, Case 2 represents modelling the sheath layer with a doubled value of copper resistivity. The sheath thickness is treated in the same manner as in the previous approach (Case 1).

Alternatively, a sheath layer thickness correction is used in order to improve the sheath layer representation by considering the effective cross-sectional area of the wired sheath [4]. In Case 3, the outer radius of the sheath is corrected according to (1) [4], where $r'_{sh1\text{-}3}$ is the corrected outer radius, A_s is the cross-sectional area of the wired sheath according to the cable datasheet, and $r_{sh1\text{-}2}$ is the inner radius of the sheath layer. Nominal resistivity of wires is used as the resistivity of the sheath layer. Fig. 2 illustrates the cable layout in Case 3.

$$r'_{sh1-3} = \sqrt{\frac{A_s}{\pi} + r^2_{sh1-2}} \tag{1}$$

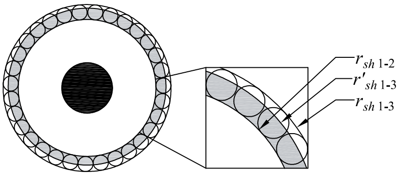


Figure 2. Cable layout and sheath layer radiuses for single layer sheath modelling approach (Case 3).

B. Equivalent Single Layer Sheath Approach

The equivalent single layer sheath modelling approach is a further improvement of the previously discussed methods. It combines both the sheath inner (wired) and outer (foil) layers into one equivalent layer and therefore corresponds more closely to the actual cable sheath design. This, however, requires additional calculations from the user. Implementing (2) [17], the sheath layer resistivity is modified by also including the outer sheath layer (aluminium foil) resistivity.

$$\rho_{eq} = \frac{\rho_{sh1}\rho_{sh2}(A_1 + A_{2)}}{\rho_{sh1}A_2 + \rho_{sh2}A_1} \tag{2}$$

where ρ_{eq} is the equivalent sheath layer resistivity, ρ_{sh1} and ρ_{sh2} are the nominal resistivity of the inner and outer sheath layers, respectively, and A_1 and A_2 represent the inner and outer sheath layer cross-sectional areas. The cross-sectional areas are calculated by (3a) and (3b) [17].

$$A_1 = \pi({r'_{sh1-3}}^2 - {r_{rsh1-2}}^2) \tag{3a}$$

$$A_1 = \pi({r_{sh2-3}}^2 - {r_{rsh2-2}}^2) \tag{3b}$$

where $r'_{sh1\text{-}3}$ and $r_{sh1\text{-}2}$ are the corrected (as in (1)) outer and inner radius of the inner sheath layer and $r_{sh2\text{-}3}$ and $r_{sh2\text{-}2}$ are the outer and inner radius of the outer sheath layer, respectively. The equivalent single layer sheath approach is illustrated in Fig. 3.

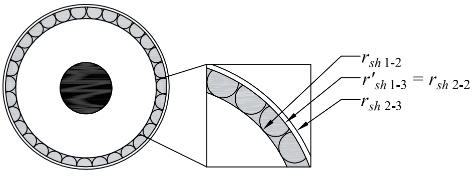


Figure 3. Cable layout and sheath layer radiuses for equivalent single layer and double layer sheath modelling approaches.

C. Double Layer Sheath Approach

At present, the most advanced cable sheath modelling approach is the double layer sheath representation [16]. In terms of the cable sheath layout (Fig. 3) and parameters, it does not vary from the equivalent single layer representation. Sheath resistivity and sheath layer radii are treated in the same manner, according to the corrected inner sheath layer and equivalent resistivity as in (1) and (2). The difference in equivalent sheath layer and double sheath layer comes from the treatment of impedance characteristics, discussed in the next section.

III. CABLE SHEATH IMPEDANCE CHARACTERISTICS

This section introduces cable sheath equivalent circuits and discusses the calculation of characteristic impedances. To analyse and compare various cable sheath modelling approaches discussed in the previous section, a comparable impedance characteristic treatment is introduced for single layer and double layer sheath approaches. Three impedance characteristics – sheath inner surface impedance, sheath mutual impedance and sheath outer surface impedance – have been defined. This enables an equivalent treatment of sheath layer components corresponding to the various modelling approaches. Only the impedance components related to the cable sheath layer have been analysed. Sheath internal and mutual impedances have been calculated based on the basic formulas for sheath impedances given in [1].

A. *Impedance Circuit for Single Layer Sheath*

For the single layer sheath representation (Case 1, Case 2, Case 3 and equivalent single layer), the equivalent circuit is shown in Fig. 4 with the following sheath related component impedances [1], [9], [16], [18]:

- Z_1, internal impedance of the inner sheath.
- Z_{sm}, sheath mutual impedance.
- Z_2, internal impedance of the outer sheath.

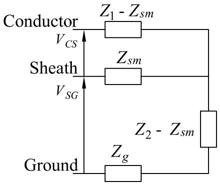


Figure 4. Equivalent circuit of single core cable with single layer sheath approach. Only cable sheath related components have been included.

The impedances Z_1, Z_{sm} and Z_2 represent sheath related components only, calculated from widely known sheath impedance formulas given in [1]. The impedances related to the core conductor, insulation and ground (Z_g) are not included in this study.

In order to compare various sheath modelling approaches, an equivalent treatment between respective impedance components is needed. Therefore, corresponding to the impedance equivalent circuit (Fig. 4), three impedance characteristic types are defined, as follows.

For single layer sheath approaches, the sheath inner surface impedance characteristic is calculated as

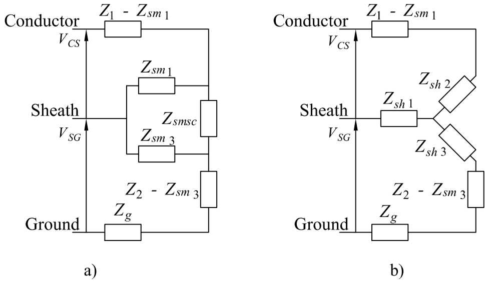
$$Z_{imp1} = Z_1 - Z_{sm}\,. \tag{4}$$

The mutual impedance characteristic for single layer approaches is simply the sheath mutual impedance, i.e. $Z_{imp2} = Z_{sm}$. The impedance characteristic related to sheath outer surface, is defined as

$$Z_{imp3} = Z_2 - Z_{sm}\,. \tag{5}$$

B. *Impedance Circuit for Double Layer Sheath*

For the double layer sheath representation, the sheath mutual impedance Z_{sm} (Fig. 4) has to be split into three components, corresponding to the wired sheath layer, semi-conductive layer and laminate sheath layer. The impedance equivalent circuit for double layer sheath approach is illustrated in Fig. 5a and 5b.



a) b)

Figure 5. Impedance equivalent circuit for single core cable with double layer sheath approach: a) delta connection and b) star connection. Only cable sheath related components have been included.

The mutual impedance of wired sheath (Z_{sm1}) and mutual impedance of laminate sheath (Z_{sm3}) are calculated by the fundamental sheath mutual impedance (Z_{sm}) formula given in [1], determined by the resistivity and thickness of the respective layer. The mutual impedances between split sheath layers, Z_{smsc} is calculated as [15]

$$Z_{smsc} = Z_3 - Z_{sm1} - Z_{sm3} \tag{6}$$

where Z_3 is given as

$$Z_3 = Z_{s1-outer} - Z_{sc-insul} - Z_{s3-inner}\,. \tag{7}$$

In (7), $Z_{s1\text{-}outer}$, $Z_{sc\text{-}insul}$ and $Z_{s3\text{-}inner}$ are the $sm1$ layer outer series impedance, semi-conductive layer series impedance, and the $sm3$ layer inner series impedance calculated by the fundamental formulas given in [1] with given sheath layer parameters. Since the thickness of the semi-conductive layer is normally less than 1 mm, the calculation of Z_3 can be simplified by neglecting the $Z_{sc\text{-}insul}$ [16].

The two conductive layers of the cable sheath are connected to each other at each cable junction and at the ends of the cable. Therefore, the delta connection in the equivalent circuit should be transformed into a star connection (Fig. 5b). The star connected impedances are calculated by the delta-star transformation as [16]

$$Z_{sh1} = \frac{Z_{sm1} \cdot Z_{sm3}}{Z_3} \tag{8a}$$

$$Z_{sh2} = \frac{Z_{sm1}(Z_3 - Z_{sm1} - Z_{sm3})}{Z_3} \qquad \text{8b)}$$

$$Z_{sh3} = \frac{Z_{sm3}(Z_3 - Z_{sm1} - Z_{sm3})}{Z_3} \tag{8c}$$

Due to the splitting of the sheath mutual impedance in the equivalent circuit (Fig. 5b), the sheath impedance characteristics for the double layer approach are defined differently. The sheath inner surface impedance characteristic is calculated as

$$Z_{imp1-d} = Z_1 - Z_{sm1} - Z_{sh2}\,. \tag{9}$$

The mutual impedance characteristic is represented by $Z_{imp2\text{-}d} = Z_{sh1}$ and the impedance related to sheath outer surface for double layer sheath approach is calculated as

$$Z_{imp3-d} = Z_2 - Z_{sm3} - Z_{sh3}\,. \tag{10}$$

IV. CASE STUDY AND RESULTS

In order to assess the cable sheath impedance characteristics between various sheath modelling approaches, a common high voltage UG XLPE cable with parametric data according to Table I, was considered.

TABLE I. CABLE DATA

Layer	Thickness (mm)	Material
Conductor	42.8[a]	aluminium
Insulation	18	XLPE, dry cured
Wire sheath	60[b]	copper
Laminate tape	2	aluminium
Outer insulation	4.45	High-density PE

a. Diameter.
b. Cross-section.

Corresponding study was made using MATLAB. Per unit impedance characteristic calculation results in frequency domain for the selected cable and for various sheath modelling approaches, are shown in Fig. 6 to Fig. 8. In Fig. 6, sheath inner surface characteristics for different sheath modelling approaches are shown. It is noticeable that the impedance characteristics approach to zero at low frequencies and in higher frequencies ($f > 10^4$ Hz), some differences are seen. In Fig. 7, sheath layer mutual impedance characteristics are shown. Here, on the contrary to the sheath inner surface characteristics, the mutual impedance characteristics approach to zero when frequency is increased. In addition, it can be concluded that the mutual impedance characteristics show higher sensitivity to the selected cable sheath modelling approach.

In Fig. 8 sheath outer surface impedance characteristics are shown. It is noticeable that the sheath outer and inner surface (Fig. 6) impedance have similar characteristics.

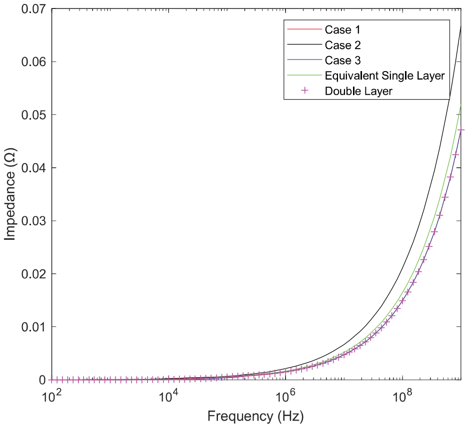


Figure 6. Frequency domain sheath inner surface impedance Z_{imp1} characteristics for various sheath modelling approaches.

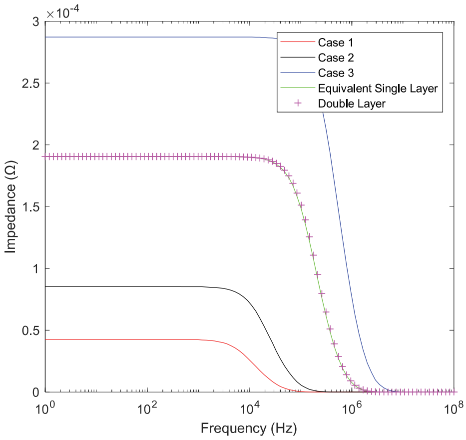


Figure 7. Frequency domain sheath mutual impedance Z_{imp2} characteristics for various sheath modelling approaches.

For the purpose of understanding the influence of different sheath modelling approaches to the level of sheath voltage in case of short circuit a study was made in PSCAD. Here, a simple three-phase high voltage (230 kV) cable with the length of 36 km and with installation depth of 1 m was considered. A single phase to ground fault was applied at cable line end point with cable loading at 20 Ω, with respective fault current of 15 kA. For the cable modelling the most accurate frequency dependent phase model was used. In the study, single layer (Case 1, Case 2, Case 3), equivalent single layer and double layer sheath modelling approaches were implemented. Results of the study are shown in Fig. 9. It is seen that differences exist between various approaches and therefore it is recommended to consider these in line/system performance analysis and in decision making process.

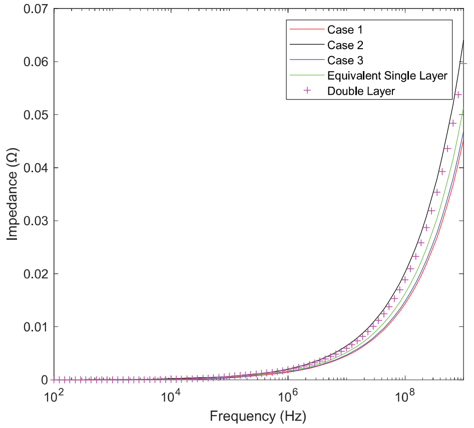


Figure 8. Frequency domain sheath outer surface impedance Z_{imp3} characteristics for various sheath modelling approaches.

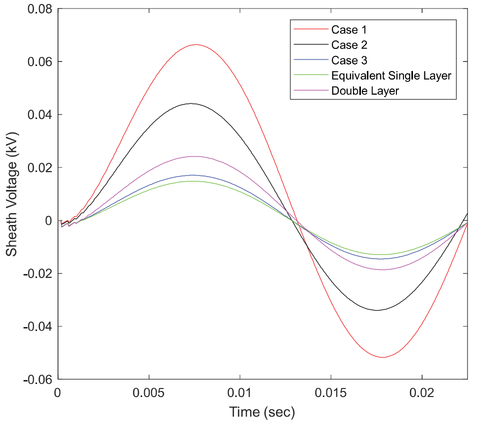


Figure 9. Sheath voltage changes in case of single-phase to ground fault considering various sheath modelling possibilities.

V. DISCUSSION

The main purpose of this study was to assess the variations between different cable sheath layer modelling approaches and evaluate the needed level of cable modelling detail when performing network studies. As the cable modelling is quite laborious work in EMT environment then additional clarifications were needed as no clear understanding on this item was available in the literature.

Frequency domain simulation results indicate that the cable sheath inner and outer impedance characteristics behave similarly, i.e. both characteristics increased when frequency reaches values over 10^4 Hz. On the contrary, the sheath mutual impedance characteristics approach to zero when the frequency reaches values over 10^4 Hz. It can be derived that the cable sheath inner and outer impedances have more influence in studies where higher frequency is of concern and sheath mutual impedance have more influence on studies where low frequency is of interest.

The significant change in impedance characteristic values at frequencies above 10^4 Hz is caused by the skin effect. Here, the current is not uniformly distributed over the conductor [18]. At lower frequencies, the current flows more evenly over the conductor cross-section, while at high frequency, the current tends to concentrate more on the conductor surface due to electromagnetic induction.

When comparing cable sheath inner and outer impedance characteristics no significant variations between different sheath modelling approaches can be seen. Only some smaller deviations due to the treatment of sheath layer radiuses can be seen. For sheath outer surface impedance characteristic, the dominant impedance component is sheath outer impedance, while for inner surface impedance characteristic it is sheath inner impedance. The sheath outer impedance is dependent on sheath layer outer radius, and whether or how its modification according to wired sheath layer is taken into account. Therefore, it can be concluded that the outer surface impedance characteristic is more sensitive to the correct sheath layer geometry representation.

Both the equivalent single layer and double layer sheath approaches consider the modified outer radius with the same sheath layer geometry. However, the difference comes from the aspect that in equivalent single layer sheath, the two conductive layers with their radiuses and resistivity are defined through sheath equivalent resistivity calculation (Eq. 2). In case of double layer sheath approach, the two sheath layer radiuses and resistivity are represented directly in outer sheath internal impedance (Z_2) calculation. Nevertheless, the variations between different sheath modelling approaches for sheath inner and outer surface impedance characteristics can be considered as minor.

The cable sheath mutual impedance characteristics presented in Fig. 7 indicate clear variation between different sheath modelling approaches. It can be noticed that equivalent single layer and double layer sheath approaches show identical mutual impedance characteristic. This is expected, considering that these two sheath modelling approaches represent cable sheath layer in most detailed extent by including the second conductive layer and are therefore most precise modelling approaches. The simple solid sheath layer approaches, Case 1 and Case 2, result in lower mutual impedance characteristics compared to the equivalent single and double layer approaches. Case 3 result in overrated impedance characteristic.

Based on the results, the sheath mutual impedance characteristics shows higher relation to the chosen sheath layer representation, since it is directly related to the interaction of two conductive sheath layers. Despite the fact that sheath mutual impedance is highly dependent on the chosen sheath modelling approach, the impedance magnitude is considerably lower (10^{-4}) than for sheath inner and outer impedance (10^{-2}). Therefore in network studies, the sheath inner and outer impedance components dominate.

Time domain EMT study results indicate that the chosen cable sheath modelling approach has an effect on the simulation results. For cable line fault case (Fig. 9), the effect on sheath voltages is noticeable. Highest sheath voltage values are obtained when single layer approaches Case 1 and Case 2 are used. The lowest voltage is obtained when single layer Case 3 and equivalent single layer approaches are used. The most precise double layer sheath approach will result in an intermediate sheath voltage value. However, the sheath voltage values for double layer, equivalent single layer and single layer Case 3 approaches are in close agreement.

From the system operator point of view, the EMT study results in case of network fault conditions indicate that using the simplified modelling approach for cable sheath will not correspond to the actual induced sheath voltage values. However, the use of simplified sheath modelling approaches results in a more overestimated sheath voltage values considering the system operational characteristics.

It is apparent that the most accurate study results will be obtained when both conductive sheath layers are included in cable model. However, in some cases this may not be possible due to the absence of correct cable data. Therefore, the selection of the sheath modelling approach for network studies begins from evaluating the available cable data. The results for equivalent single layer and single layer Case 3 approach are in close agreement and also comparable with double layer approach results. This indicates that in case when there is no data available on the compound sheath layer parameters, it can be suggested that for acceptable study results single layer Case 3 approach should be implemented. However, when the decision is made on the most robust sheath modelling approach (Case 1 or Case 2), respective deviation in study results should be considered.

VI. CONCLUSION

This paper presents the results of the assessment of various high voltage UG XLPE cable sheath modelling approximations used for cable modelling in EMT studies. Based on the assessment it can be concluded that accurate cable sheath modelling is important and affects the study results. Therefore, engineers performing the studies should acknowledge the cable sheath characteristics, such as its layered structure and material parameters, and when possible use the most complete modelling approaches that considers cable sheath as compound layer. However, there are various aspects influencing the selection of the modelling approach starting from the availability of data and type of the study, e.g. high frequency phenomena assessment. As an alternative modelling approach, the single layer approach where effective cross-sectional area of the wired sheath is considered (Case 3), is recommended. When the most simplified modelling approaches, the solid single sheath layer with nominal resistivity (Case 1 and Case 2) are implemented, the deviations in study results needs to be considered.

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Triin Kangro was born in Otepää, Estonia, 1989. She received the B.Sc. and M.Sc. degrees in electrical engineering from Estonian University of Life Sciences and Tallinn University of Technology (TUT), Estonia, in 2011 and 2013, respectively. Since 2013, she is a PhD student at TUT. Currently she is working at the Department of Electrical Power Engineering of TUT as a researcher.

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