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*Publication date:*
2015

*Document Version*
Publisher's PDF, also known as Version of record

*Citation for published version (APA):*
Bak, C. L. (2015). *EHV/HV Underground Cable Systems for Power Transmission*. Department of Energy Technology, Aalborg University.

# EHV/HV Underground Cable Systems for Power Transmission

A PhD dissertation by Claus Leth Bak

December 2014

DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

**Thesis title:** EHV/HV Underground Cable Systems for Power Transmission

**Name of the PhD student:** Claus Leth Bak

**Name of Supervisor:** John K. Pedersen

**List of published papers:**

[1] Claus Leth Bak, Wojciech Wiechowski, Kim Søgaard and Søren Damsgaard Mikkelsen, Analysis and simulation of switching surge generation when disconnecting a combined 400 kV cable/overhead line with shunt reactor, IPST 2007.

[2] F. Faria da Silva, Claus L. Bak, M. Lind Hansen, Back-to-Back Energisation of a 60kV Cable Network - Inrush Currents Phenomenon, IEEE-PES GM 2010.

[3] Claus L. Bak and Christian F. Jensen, Distance Protection of Cross-Bonded Transmission Cable-Systems, DPSP 2014 BEST PAPER AWARD.

[4] F. Faria da Silva and Claus Leth Bak, Electromagnetic transients in power cables, 1st Edition, Springer 2013.

[5] F. Faria da Silva, W. Wiechowski, C. Leth Bak, U. Stella Gudmundsdottir, Full Scale Test on a 100km, 150kV AC Cable, paper B1-301 Cigré General session 2010.

[6] Michal Sztykiel, Claus Leth Bak, and Sebastian Dollerup, Line Differential Protection Scheme Modelling for Underground 420 kV Cable Systems, EMTDC/PSCAD Relays Modelling, International Protection Testing Symposium, 2011.

[7] Claus Leth Bak, Wojciech Wiechowski, Kristin E. Einarsdottir, Einar Andresson, Jesper M. Rasmussen and Jan Lykkegaard, Overvoltage Protection of Large Power Transformers – a real life study case, ICLP 2006.

[8] Claus Leth Bak, Kristin Erla Einarsdóttir, Einar Andresson, Jesper M. Rasmussen, Jan Lykkegaard, and Wojciech Wiechowski, Overvoltage Protection of Large Power Transformers—A Real-Life Study Case, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 23, NO. 2, APRIL 2008.

[9] F. Faria da Silva, C. Leth Bak and P. B. Holst, Study of Harmonics in Cable-based Transmission Networks, C4-108 Cigré General Session 2012.

[10] C. Leth Bak and F. Faria da Silva, High Voltage AC underground cable systems for power transmission – a review, part 1, Journal of Electric Power System Research, 2015 (submitted – under review).

[11] C. Leth Bak and F. Faria da Silva, High Voltage AC underground cable systems for power transmission – a review, part 2, Journal of Electric Power System Research, 2015 (submitted – under review).

[12] C. Leth Bak, S. D. Mikkelsen and C. Jensen, Overhead line audible noise measurements and calculation model for snow and frosty mist, ISH 2005.

This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty.

**Public defence of PhD dissertation**

**Thesis title:** EHV/HV Underground Cable Systems for Power Transmission

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Pontoppidanstræde 101, Room 23, Department of Energy Technology, Aalborg University

**ISBN:** 978-87-92846-54-9

*Dedicated to*

*The loving memory of my Mother*

*My daughters Freja and Frida*

*My fiancée Tine*

*And the Cats!*

## Preface

This PhD study is an unusual one. I have been working with electric power engineering for 20 years, both in the industry for 5 years and in my present position at the Department of Energy Technology at Aalborg University, where I have held a professor position since 2011.

The main motivation for the study is to acquire the PhD degree in order to formally be at the same academic qualification level as my professor colleagues both at Aalborg University and worldwide.

Through the years, I have been fortunate to work with various, always interesting and exciting topics; hence, it came natural to select one of the promising candidates of the topics I have researched and base a PhD thesis (collection of already published papers) upon this.

The core research area of the present thesis is underground cables in the transmission system. In this area, I have been doing research together with Danish TSO Energinet.dk for at least 10 years and the thesis is based on selected publications from this period, trying to cover the most interesting and practically useful results obtained through the years.

As already stated, this PhD dissertation is an unusual one with regards to the approach. A PhD student usually works in a concentrated manner for 2½ years (the last 6 months consists of courses and teaching) typically upon one very well-defined topic such as i.e. a time domain model for underground cables. The research results of my dissertation span over longer time and cover a larger variety of topics being researched than a usual PhD. This is due to the fact that the results in my dissertation to a larger degree are obtained through cooperation between me and my co-authors with whom I in every single case have contributed to the overall progress in underground cable research, thus leading to a larger number of research results as compared to an ordinary, typical PhD study. When this is said, I owe my sincere acknowledgement to all my cooperating co-authors through the years where underground cable research results have been collected – the results presented in this thesis would not have been possible without your valued skills and cooperation.

Hence, my claim for applying for the PhD degree is not with regards to acquiring every single detailed research result presented in this thesis, but the overall research management of a long-lasting research project, which I have originated together with Energinet.dk and led to success with regard to many obtained research results, enabling a practical use of underground cable systems for power transmission.

This thesis is made up of a collection of papers, constituting a short summary of their main findings. These papers may be found in the last part of the thesis. The main writings of the thesis consist of results published in the two review papers “High Voltage AC underground cables for power transmission – a review, part 1 and part 2 [10] and [11] and the book “Electromagnetic transients in power cables” [4]. These publications summarise the research results related to the use of underground cables in the transmission system, obtained in the last 10 years at Department of Energy Technology, Aalborg University, in cooperation with Danish TSO Energinet.dk

References are marked with [xx] and may be found in chapter 7. References marked as {yy} in [xx] are a reference numbered as yy in reference xx of this thesis.

The reference background for the state-of-the-art of this thesis is available through [10] and [11] as these are review papers reviewing the research upon which this thesis is based. They use 39 references in which I am the author/co-author. Further references are to be found in the references of these 39 publications and the remaining references listed in [10] and [11] of which I am not the author.

Through my life in engineering, I have many people to thank – so many that a comprehensive list inevitably would miss a few. Therefore, my grateful thanks go to:

- My numerous professionally very skilled and good colleagues at Energinet.dk
- My colleagues at the Department of Energy Technology at Aalborg University
- Dr Wojciech Wiechowski, Dr Søren Damsgaard Mikkelsen and MSc Kim Søgaard for being the forward-looking initiators of cable research
- My co-authors of the publications
- Anyone with whom I have had professional cooperation in High Voltage and Power Systems through the years
- The assessment committee for assessing the thesis and conducting the defence
- Professor Frede Blaabjerg for good advice and source of inspiration
- Head of department John K. Pedersen for supporting this process
- Head of doctoral school professor Dr Tech. Torben Larsen for valuable guidance
- My very good, close colleague Associate Professor Filipe Faria da Silva for always brilliant and ingenious contributions to our common work

A proper final word comes to my mind, because it has followed me and my career for many years:

*DIE MODERNE KULTUR BERUHT AUF DER HERRSCHAFT DES MENSCEN*

*ÜBER DIE NATURKRÄFTE UND JEDES NEU ERKANNTE NATURGESETZ*

*VERGRÖSSERT DIESE HERRSCHAFT UND DAMIT DIE HÖCHSTEN GÜTER UNSERES GESCHLECHTES*

*by Werner von Siemens, founder of Siemens (http://dingler.culture.hu-berlin.de/article/pj331/ar331085)* or to be found in the front page of the book "Die Entwicklung der Starkstromtechnik" bei den Siemens-Schuckertwerke "Zum 50 Jährigen Jubiläum".

Claus Leth Bak

Hammer Bakker

December 2014.

## Abstract

Power transmission is facing its largest challenges ever with regards to handling a transition from today's fossil-based power production into renewable sources of generation. We can no longer place power plants close to centres of consumption; they must be located where the natural resources are to be found. One very good example of this is offshore wind power plants.

The current transmission system is laid out in a traditional manner, which is based on the idea of not transporting power over longer distances as the power plants have been located near centres of consumption. It has merely played the role of interconnecting these generation/load centres, ensuring fair reliability and redundancy of supply.

Nowadays, the power transmission system must be able to handle the various sources of renewable generation in a flexible electricity market. This has the consequence that the original layout of the transmission system must be re-thought in order to accommodate the transmission needs for the future. New lines have to be constructed.

Transmission lines are usually laid out as overhead lines, which are large structures, i.e. a 400 kV power pylon is 50 meters high. According to public opinion, such power lines are undesirable. Therefore, we must come up with an alternative, acceptable to the public.

Underground cables fulfil the above mentioned need to be more publically acceptable, but, for long transmission lines, they are in many ways unproven. Guidelines for their design are needed.

This thesis presents the results of a decade of underground cable research studies performed in Denmark by Danish TSO Energinet.dk and the Department of Energy Technology.

The thesis is based upon a number of selected publications and summarises the results of these at a presentation level intended to have an easier, possibly less scientific touch. The results are taken from their scientific embedding in the papers and made more easily accessible to readers of the thesis. The full theoretical background is to be found in the papers and their references.

Firstly, an introduction to the challenges when using underground cables is given, and secondly, the modelling approach and validation of this is discussed. Thirdly, making up the main core of the work presented, dynamics of underground cable systems are discussed and important cases to study are highlighted, and next, protection and fault location are discussed. The thesis ends with conclusions and future works, a bibliography and the publications upon which it is based.

It is concluded that underground cable systems are technically possible for power transmission, although the maturity of the consequences of the newly made design guidelines are still in its youth. Many interesting research topics are still open, especially with regards to asset management tools.

## Danish Summary

El transmissionsnettet står overfor den største udfordring nogensinde når den voksende mængde af fornybare el-produktionsanlæg skal erstatte de nuværende, der er baseret på afbrænding af fossile brændsler. Det er ikke længere muligt at placere kraftværker tæt på store forbrugscentre såsom byer og industrianlæg. Disse må nødvendigvis placeres der, hvor de fornybare ressourcer er tilgængelige. Et eksempel herpå er offshore vindkraftværker.

Transmissionsnettet er traditionelt designet til ikke at skulle overføre store mængder energi over lange og varierende strækninger, i det el-produktionen var lokaliseret hvor forbruget også var. Transmissionsnettes rolle har mere været som et samarbejdsnet, der har sikret en rimelig pålidelighed og redundans med hensyn til forsyning.

Fremtidens transmissionsnet skal kunne håndtere de mange forskellige og effektvarierende fornybare el-produktionsanlæg, der planlægges og samtidig kunne fungere på markedsvilkår. Dette medfører, at transmissionsnettets nuværende topologi skal gentænkes for at kunne opfylde fremtidens krav til transmissionsnettet. Der skal bygges nye linjer.

Transmissionslinjer udføres normalt som luftledningsanlæg, der er vældig store og dominerende i deres omgivelser. For eksempel er en 400 kV luftledningsmast 50 meter høj. Befolkningen udviser en langvarig og stigende utryghed overfor luftledningsanlæg og modstanden mod nye anlæg er massiv. Vi er nødt til at komme med alternativer til luftledningsanlæg, som befolkningen kan acceptere. Nedgravede kabelanlæg opfylder dette ønske, men er på mange måder uprøvet teknologi for el-transmission. Der er behov for ny forskning for at kunne skabe de retningslinjer, som et teknisk forsvarligt design af sådanne bygger på.

Denne afhandling præsenterer 10 års forskningsresultater for kabeltransmissionsnet for et forskningssamarbejde mellem den danske transmissionssystemoperatør Energinet.dk og Institut for Energiteknik, Aalborg Universitet. Afhandlingen er baseret på et antal udvalgte publikationer, og den summerer og fremhæver resultaterne fra disse på et formidlingsniveau, der er tiltænkt som værende lettere tilgængeligt end den videnskabeligt "normale" formidling i publikationerne. Dette giver mening, da afhandlingen præsenterer mange resultater fremfor detaljerne i enkelte resultater, hvorfor disse må skulle formidles bredere. Resultaterne er valgt fra deres videnskabelige kontekst i publikationerne og søgt formidlet, så de er nemmere tilgængelige for denne afhandlings læsere. Den fuldstændige beskrivelse af baggrunden for hvert enkelt forskningsresultat kan findes i publikationerne.

Først gennemgås de tekniske udfordringer, som opstår, når man vil anvende kabler til el-transmission, derefter modeldannelse og validering i tidsdomænet, derefter følger hovedvægten af det udførte arbejde, hvilket er dynamiske forhold for kabeltransmissionsanlæg. Der opstilles teori og eksempelstudier for de forskellige designstudier, der skal gennemgås, for at et komplet design kan gennemføres. Herefter gennemgås beskyttelse og fejllokalisering og afhandlingen afsluttes med konklusion og forslag til fremtidigt arbejde. Til slut findes en litteraturliste samt de publikationer, afhandlingen er baseret på.

Det konkluderes, at nedgravede kabelanlæg er en teknisk mulig løsning til el-transmission, selv om konsekvenserne af ovennævnte, nye designregler ikke er kendt på langt sigt. Der fremstår mange interessante, fremtidige forskningsemner, specielt indenfor asset management værktøjer.

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## List of abbreviations

TSO: Transmission System Operator

DC: Direct Current

AC: Alternating Current

OHL: OverHead Line

TRIPLEX: Phase conductor consisting of three sub-conductors

UGC: Underground Cable

XLPE: Cross-linked PolyEthylene

CB: Circuit Breaker

R: Resistance

L: Inductance

C: Capacitance

X: Reactance

Z: Impedance (Z1 positive sequence, Z2 negative sequence and Z0 zero sequence)

IC: Current in conductor (phase)

ISH: Current in sheath

IG: Current in ground

IM: Measured current

GMD: Geometric Mean Distance

TOV: Temporary OverVoltage

GIS: Gas Insulated Substation

ARC: AutoReClosure

SR: Shunt Reactor

HVDC: High Voltage Direct Current

LCC: Line Commutated Converter

$\tau$: Travel time

FD: Frequency Dependent

FDNE: Frequency Dependent Network Equivalents

SLG: Single Line to Ground

k0: Zero sequence compensation factor

ECC: Earth Continuity Conductor

v: Speed

l: Length

Cigré: Conseil International des Grands Réseaux Électriques (International Council on Large Electric Systems)

SC: Study Committee (in Cigré)

## 1. Introduction to the challenges of using underground cables in the transmission network

Electricity is characterised by having to be produced in exactly the same instant as it has to be used. Furthermore, electric power is not an easily accessible article. It cannot be collected easily as for instance firewood for heating. Electric power is not a resource readily available, we must use rather complicated devices relying on natural science principles to produce electric power by consuming or sampling energy from other sources (fossil, solar, wind, nuclear) and converting into electric power. For most of the power needed by modern society, this conversion is undertaken in power plants. They have traditionally been large, centralised plants, generating electric power by converting fossil fuels or nuclear reactions into mechanical power by means of a steam turbine which in turn powers an electric generator. Recent development in society tends towards including an increasing amount of renewable sources in the production of electric power in order to reduce carbon dioxide emission. The most prominent plants of today are offshore wind power plants and solar power.

Modern society demands a huge amount of electric energy to be generated and made available to the consumers. This makes it necessary to operate a number of generating plants, of which a fair mixture of non-constant producing sources such as wind and solar are supplemented with controllable sources such as thermal power plants in order to always assure the availability of power.

The transmission network undertakes a paramount role in being the almost uninterruptible transport pathway for electric power to be transmitted between the generating plants and the consumers. Throughout the last century, transmission lines have almost exclusively been laid out as overhead lines (OHL). The visual impact of OHL is very dominant and an increasing resistance in the public opinion against OHL has been growing the last 20-30 years, causing it to be very difficult for transmission system operators TSO to get the governmental permission to build new lines. Audible noise from OHL, which is due to corona [12], adds to this negative attitude among people. This is often due to subjective, thinking like “devices emitting this kind of noise must be dangerous”, so people are scared by OHL and do not want to live or stay near them.

The methods and results in [12] have resulted in the design of a new transmission power pylon, the EAGLE pylon, which is used for the Jutland – Germany 420 kV backbone. The phase conductor design employs a TRIPLEX phase conductor. This has resulted in a more quiet transmission line.

The building of new lines is a must in order to make the transmission system able to handle the integration of renewable sources of power generation. For Denmark, the transmission network has been laid out with a topology linked to power generation at large central power stations and transmission of power to the load centres (cities) by means of a meshed network connecting to Germany (AC), Sweden and Norway (DC). The predominant power flow has been mainly north-south, but the inclusion of offshore wind in Jutland, mainly at the west coast, tends to state a need for power to be transmitted west-east. Hence, a need for building new transmission lines emerges as the renewable sources are being put into operation.

A more publically acceptable alternative to OHL has become an almost indispensable key to enabling the transition of the transmission system to handle the renewable sources of power generation. The only alternative to OHL is underground cables UGC. Such have to date been used very sparsely for voltage levels of the transmission system and almost solely as mass-impregnated cables. State-of-the-art technology is

XLPE cables which are being manufactured for voltage levels such as 420 kV, 220 kV and 170 kV and for both onshore and offshore use. Main usage is for transmission power to enter large cities like Tokyo. Also, there is a tradition in Denmark for using UGC when having substations and/or power plants in urban areas.

The widespread use of UGC in the Danish transmission network became reality when Energinet.dk (TSO) published the cable act plan in 2008. This report compared six different scenarios with regards to the future grid expansion and spanning from “no grid expansion” to a “complete undergrounding” for the 420 kV transmission network. An intermediate choice was selected where basically all new 420 kV lines are laid down as UGC. The 170 kV network will undergo a complete undergrounding. The plan is to be realised within the next 20 years.

Today’s electric power system is by many considered as the most complicated and largest man-made machine, and the challenges it faces in the years to come due to the integration of renewables are almost revolutionary.

Introducing the underground cables in the transmission system as described above with their much different electrical characteristics and thereby a type of behaviour not at all similar to OHL, makes the transmission system even more complicated.

In Denmark, which is a densely populated country with a politically conscious population, the pressure against OHL has for many years been so vivid that new measures had to be taken to be able to approve new transmission lines.

The first real attempt to do this was realised via the plans for interconnecting the cities of Aarhus and Aalborg with a 400 kV transmission line. The governmental reading and hearing and approval of such a new 92 km transmission line took more than 10 years, and it was not approved before the planned OHL was replaced with two underground cable sections, one 2.8 km section when crossing a fjord (Mariager Fjord) and another 4.5 km section when crossing an area of natural beauty (Gudenaa River).

The line layout can be seen in figure 1.

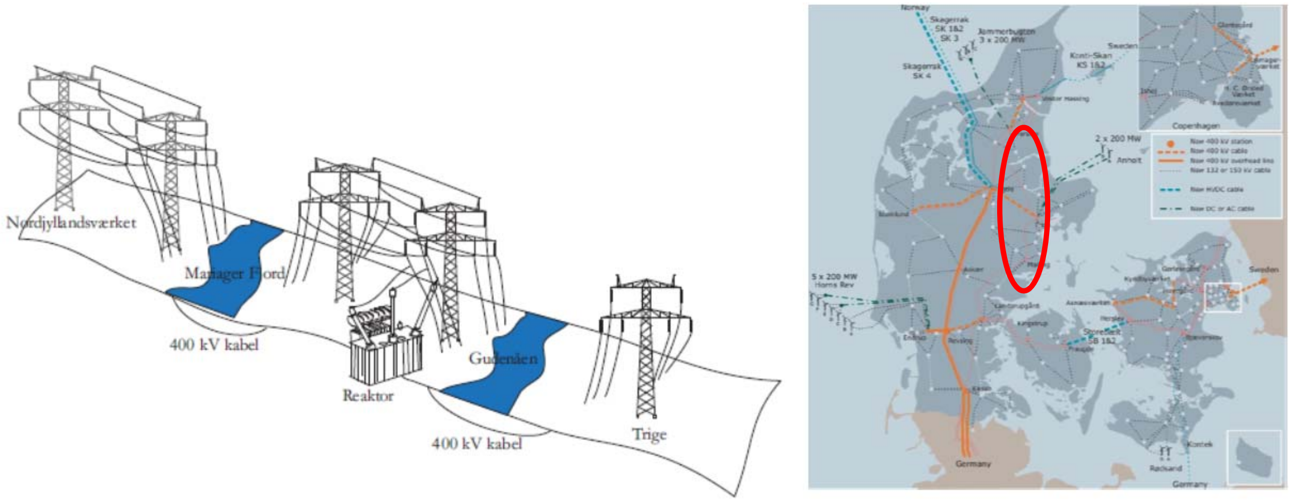

Figure 1: New 400 kV transmission line between the cities of Aarhus and Aalborg, having two underground cable sections when crossing areas of natural beauty [1].

As can be seen in Figure 1, the line consisted of two cable sections with two systems each (i.e. 2x3 cables), one permanently connected shunt reactor for reactive power compensation of the cable sections and of three OHL sections of which one section of 25.9 km was erected on a new type and design for a 400 kV transmission tower, see Figure 2. This design was adopted on the basis of a design competition, which lead to the proposed, new design. This was another means to getting a better public acceptance of the new line.

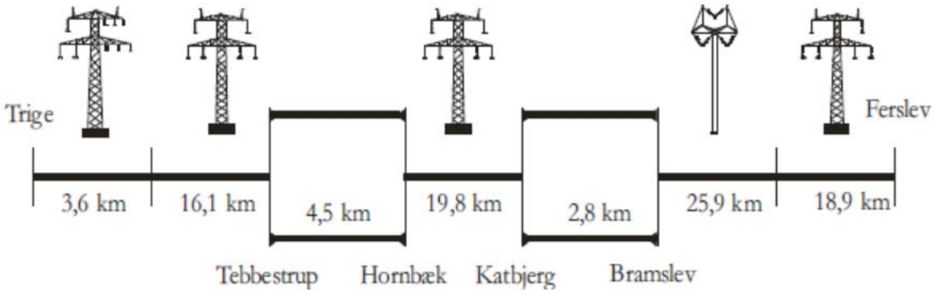

Figure 2: Schematic of the Aarhus – Aalborg 400 kV line between substations TRIGE and FERSLEV [1].

The line was erected and tried energised for the first time in 2004. Danish TSO Energinet.dk did not at that time have much experience with such hybrid lines. With that in mind, it was decided to monitor voltages and currents in both the sending end and the receiving end by means of transient recorders during switch on, no load, load and switch-off. Nothing special was reported when switching on, except for the DC offset caused by the shunt reactor, but this was anticipated. However, when switching off, rather unknown (at that time) phenomena were recorded. This is shown in Figure 3 below.

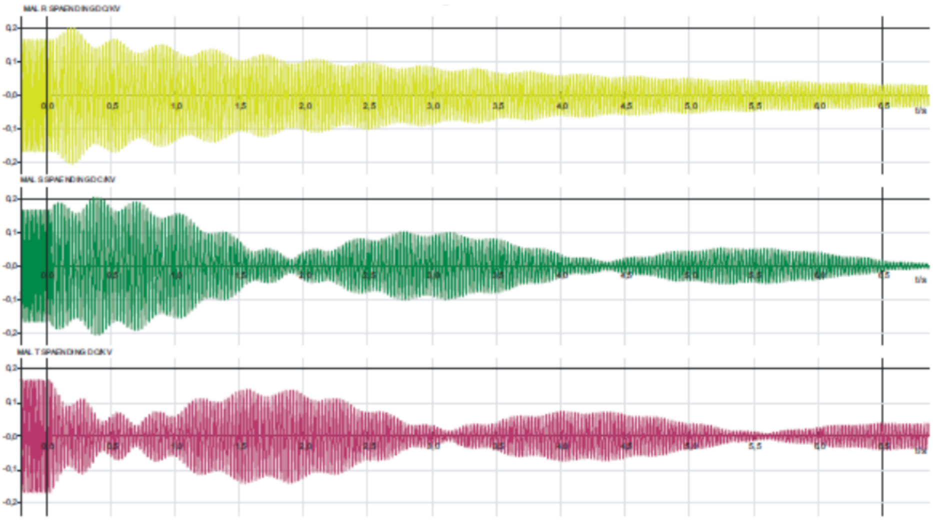

Figure 3: Phase voltages for the 400 kV line NVV-TRI when performing last-end disconnection. Time scale horizontal 6.5 s between bars and voltage peak before instant of switching (before left bar) is equal to 335 kV [1].

Last end switch-off voltages clearly showed different modes of oscillating phenomena as well as overvoltage lasting for seconds, see Figure 3. Such electrical behaviour was unknown at the time and thus never been seen before by Danish TSO Energinet.dk

In order to be able to operate transmission lines, including underground cables, in a secure manner, it was necessary to fully understand this behaviour. The initial analysis of the physical causes of the oscillating modes shown in Figure 3 is described in [1]. The main findings are (cited from [1]):

"• When switching the line off the 50 Hz system, it will start resonating with a frequency equal to its resonant frequency given by its inductances and capacitances, which are dominated by the shunt reactor inductance and the cable capacitance. In this case, this frequency is around 35 Hz.

• The differences in appearance for the three phases is due to the slightly different resonant frequencies of each phase (caused by reactor and line asymmetries), which are coupled by mutual couplings (also unsymmetrical, both inductive and capacitive, or just inductive, as the phenomenon was also registered in a pure cable line [5]) between phases and thereby added. Adding two sinusoidal with slightly different frequency yields such low-frequent modulations. In this way, numerous shapes and appearances (frequencies, amplifications, attenuations) of last-end switch off voltage decay can form [1] and [11].

• The overvoltage stems from the summation of both the capacitive and inductive induced voltages as the frequencies are slightly different per phase and thereby, the induced voltages in one phase (from the other two) will either more or less add to the phase voltage and thereby add to the phase voltage increasing it or subtract from the phase voltage lowering it [1], [11] and {7} in [10].

• The fact that the three phases are not switched off at exactly the same time, due to current interruption in current zero in the circuit breaker, adds to the non-aligned adding of the phase voltages."

A further question came up, as single-phase autoreclosure is used for the overhead line part. Suppose the feeder protection opens one phase due to a fault, could we expect that the energy induced into the switched-off phase would be sufficient to maintain the fault arc and thereby preventing a successful autoreclosure? [10].

*Summary*

Undergrounding the transmission system makes the electrical behaviour of this much different compared to an OHL system. The electrical characteristic of cables results in their dynamics to be different as compared to OHL. The entire design foundation for a transmission line, including reactive power compensation, simulation models, transient studies, protection and fault location must be revised in order to be able to design undergrounded transmission systems with a confidence and reliability similar to OHL.

***Main hypotheses***

- Is it possible to put up a complete set of tools and guidelines which enable analysis and assessment of underground transmission cable mode of operation and with such level of detail and confidence that we ultimately can design such cable transmission systems as easily and as reliable as conventional overhead lines?

## 2. Modelling of Underground Cable Systems

The first question to put up before starting to design an undergrounded transmission system is the proper selection of simulation tools which can be trusted to give realistic and correct results.

The steady state load flow studies for assessing power flow and selecting reactive compensation patterns as well as voltage profile are usually conducted using power flow tools such as DigSilent Power Factory or similar software.

The challenges in assessing their validity are not severe; such tools mainly rely on a proper calculation of electrical constants used to simulate lines as discrete elements (R. L and C) equivalent schemes in symmetrical loads.

The insulation coordination studies need time domain simulation tools such as PSCAD/EMTDC or similar types of software to be able to simulate various switching conditions as well as lightning current ingress into the transmission lines. Furthermore, the selection of surge arresters mostly relies on proper time domain simulations.

However, this immediately raises the question: can we trust the simulation models for cables to give correct results for the complicated electrical behaviour of an undergrounded, cross-bonded cable transmission system?

Transient models for OHL are widely used and have been proved valid through many years. This is not the case for underground cable transient simulation models as the use of underground cables up until the millennium has been rather limited. Models are available, but they have been sparsely used and - up to the point of this research study - not validated against real-life dynamic measurements on installed transmission cable systems [10], [13].

Cables can be modelled by simple means such as pi-sections for steady state studies, but an accurate representation of several frequencies needs frequency dependent time domain models.

The only realistic and trustworthy way to validate such complicated numerical models is by using high quality real-life, full-scale measurements and compare these to the similar case simulation cases.

### *2.1 Field measurements of undergrounded transmission cable systems*

Field measurements have been conducted on a 7.6 km 400 kV cross-bonded cable laid in flat profile [10] as shown in Figure 4.

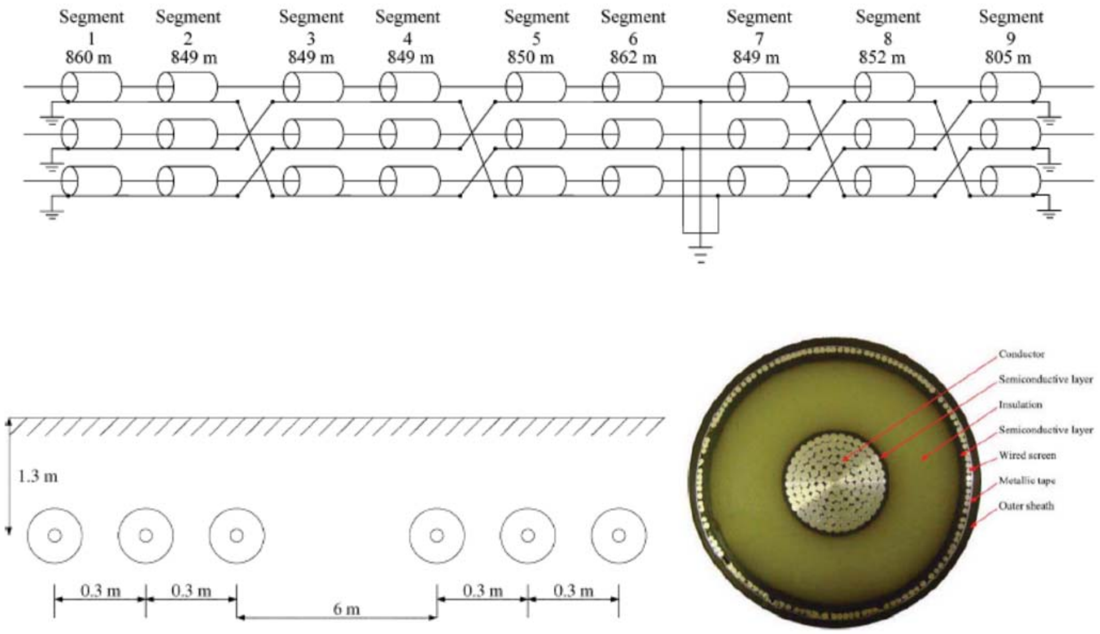

Figure 4: Layout of the cable used for field measurements [10].

One of the outer phases is energised by a lightning impulse generator in order to inject a high frequency containing voltage, which is expected to excite the frequency dependent behaviour of the cable and thereby form a result that we can use for validating the numerical frequency dependent underground cable simulation model. Full details are available in [10] and references listed in the same, for instance {20} in [10].

To give an example of such measurement results and their usefulness in validating cable model, both phase quantities and modal quantities obtained after modal transformation are shown in Figure 5.

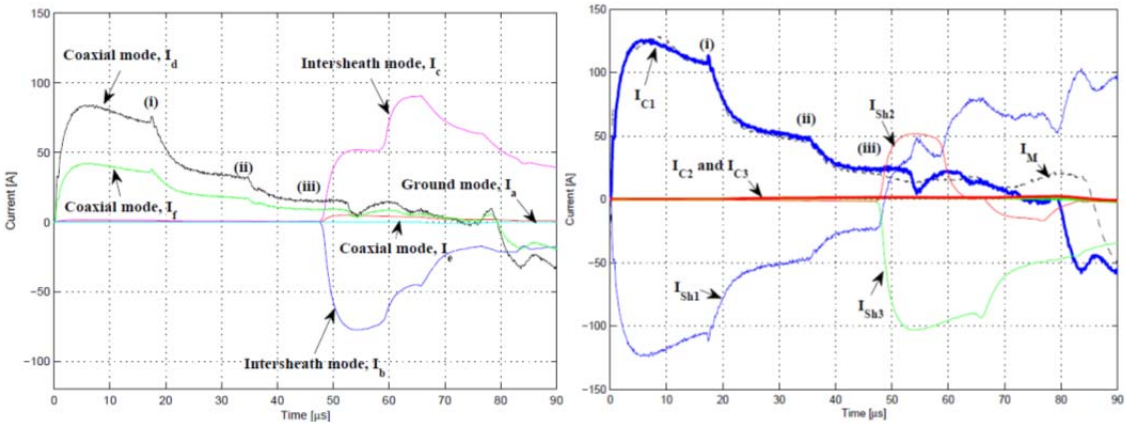

Figure 5: Modal quantities (left) and phase quantities (right) of the measured cable receiving end [10].

After approximately 50 µs, deviation appears between measured receiving end current (black curve in figure 5, right) and PSCAD/EMTDC simulated receiving end current (blue curve in figure 5, right). This is due to the initiation of the intersheath mode current at exactly the same instant (pink curve in figure 5, left). It can be concluded that the presence of the intersheath mode current, which is caused by the actual current distribution in the sheaths, causes the inaccuracy occurring at 50 μs.

The current distribution in the sheaths is dependent upon proximity effect which is not modelled in the simulation model due to the fact that the models available do not include proximity effect. Furthermore, the screen (sheath) is modelled as a solid coaxial shell, which is not in accordance with the real cable screen physical layout. This is made of a number of spiralling conductors and semi-conductive layers and is thereby not properly represented by a simple structure such as the solid coaxial shell.

*2.2 Underground cable model improvement*

From 2.1, it is obvious that a better physical modelling of the screen in the cable must contribute to better intersheath current mode accuracy and thereby an overall more accurate high-frequency cable model.

The model improvement is conducted in two steps [10]:

- Layering of the screen is modelled accurately. This results in a better high-frequency damping
- Proximity effect is included using a new concept dividing the screen conductors into exponentially distributed sub-conductors and calculating self- and mutual GMD

The effect of this modification of the model is implemented in a MATLAB model together with the frequency dependent cable model and compared to PSCAD/EMTDC simulations with the non-corrected frequency dependent phase model as well as measurement results. It is evident that the inclusion of screen layering and proximity effect improves the accuracy of the underground cable model, see Figure 6.

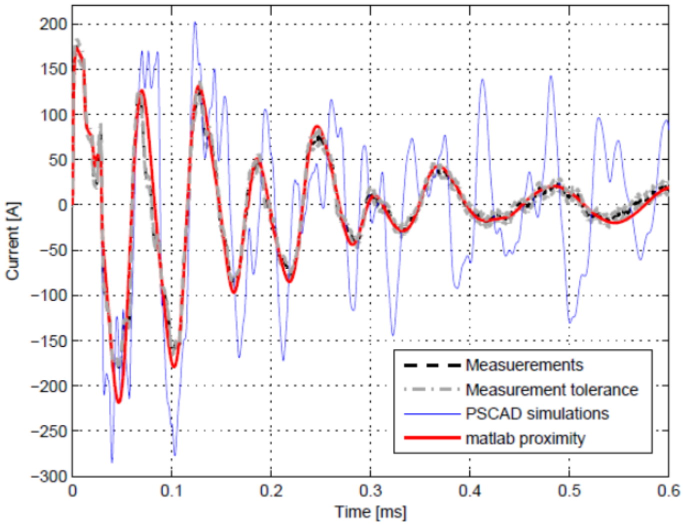

Figure 6: Comparison of measured (black) sending end current with PSCAD simulation (blue w/o corrections) and MATLAB simulations (red w corrections) for sending end of energised major cable section [10]

*Summary*

The main findings of the underground cable model studies reveal that the frequency dependent cable models available in time domain simulation software can be trusted and be used for usual transient simulation studies such as switching overvoltage. Including screen layering and proximity effect yields better intersheath mode accuracy.

## 3. Dynamic Studies for Underground Cable Systems

Insulation coordination studies for transmission systems employing underground cables in either hybrid type lines (OHL and cable in series) or as full length cable lines must undergo transient simulation studies in order to assess the magnitude of temporary overvoltage (TOV), switching overvoltage and lightning overvoltage (when applicable). Furthermore, without careful pre-studies, we cannot know which phenomena to analyse by means of simulations as we do not have experience-based knowledge of the cases prone to providing worst case overvoltage. Therefore, as a start, it is necessary to make a list of foreseeable overvoltage analysis studies to be conducted in order to be able to complete a sufficient insulation coordination study. These cases are described in [10] and [11] and in detail in the references listed there. The following provides the main findings within each of the subcategories able to create overvoltage.

### *3.1 Resonances*

TOV caused by resonances are more likely to occur in a cable-based transmission system due to the presence of shunt reactors and the much larger shunt capacitance as compared to OHL. Therefore, we must expect phenomena such as energisation of transformers and cables, fault clearing, load shedding and system islanding to result in long-duration TOV's. Such TOV's must be well-known in order to be able to design surge arrester energy absorption capability.

### 3.1.1 Series resonances

Series resonance can be excited by energising a cable in the vicinity of a series resonant circuit such as another cable which is fed through a transformer. In this way, transformer leakage inductance is in series with cable shunt capacitance. Such an example is shown in Figure 7 together with its voltage waveforms, showing the TOV as phase to ground voltage in a 132 kV network.

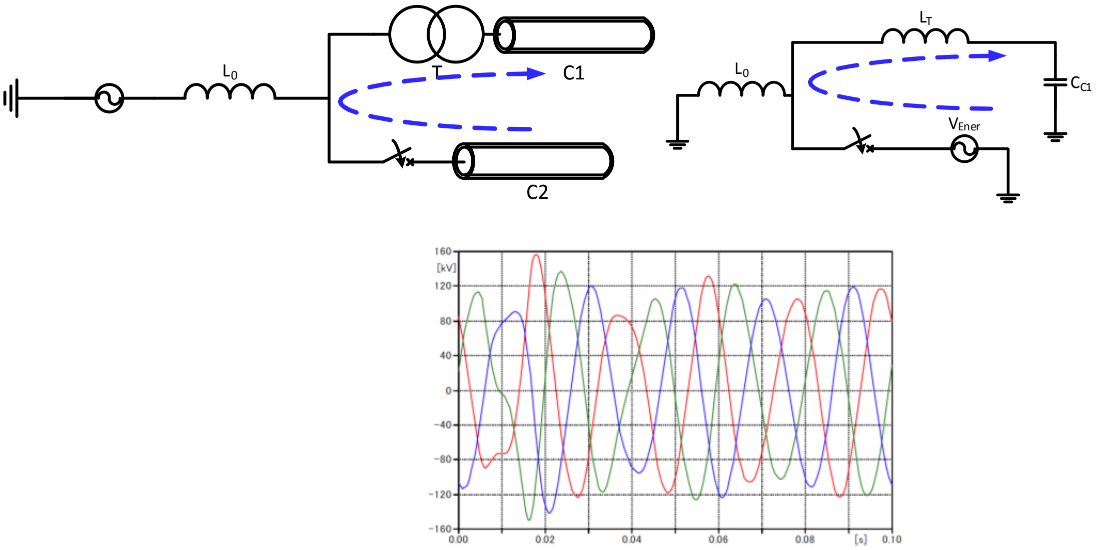

Figure 7: Example of series resonant principle (upper) and the TOV in a 132 kV network (lower) [10]

An operating voltage of 132 kV yields a phase to ground voltage around 76 kV so TOV of more than 50% is present in the case illustrated in Figure 7.

### 3.1.2 Parallel resonances

A typical example of a parallel resonance circuit is the energisation of a transformer connected to a weak network by means of a long cable. Such a setup is expected to create long duration, low frequency TOV with almost no damping due to the very high quality factor of the transmission network. This is illustrated in the example shown in Figure 8.

As can be seen in Figure 8 (lower), high magnitude TOV (2.15 p.u. assuming 400 kV operating voltage) is generated when energising a transformer through a cable.

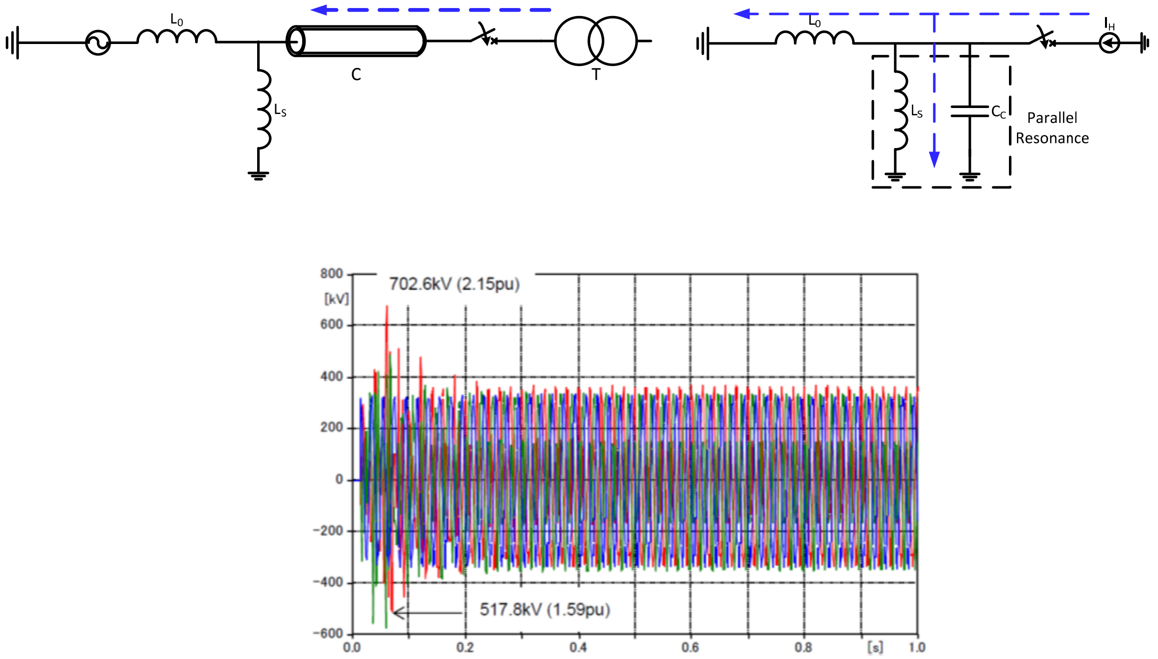

Figure 8: Example of parallel resonance principle (upper) [10] and the TOV in a 400 kV network energising a transformer (lower) {13} in [10]

### *3.2 Fault clearing and system islanding*

When faults are cleared and thereby, parts of a transmission system are isolated, transient voltages are created. These depend on system parameters and contain both power frequency and an excited resonant frequency [10]. Figure 9 shows an example of such a case.

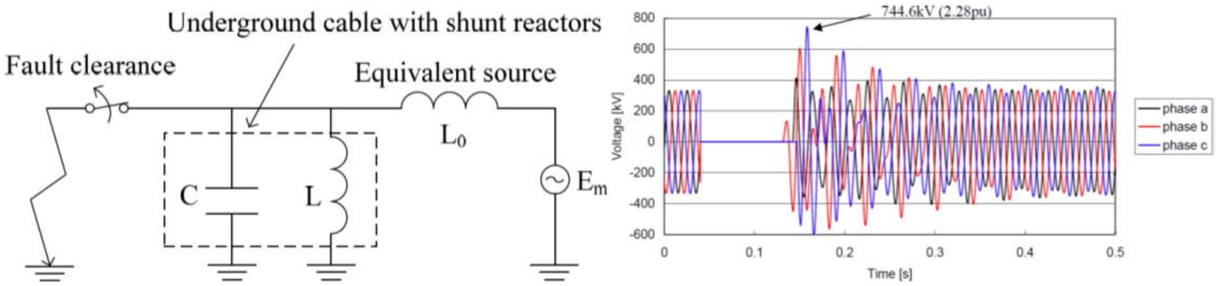

Figure 9: Equivalent circuit of fault clearance (left) and an example of an overvoltage caused by a busbar fault leading to system islanding [10].

System islanding is less likely to happen in strong, meshed networks. An exception is the radial connection of offshore wind farms which have proven to lead to large TOV's [10].

*3.3 Energisation*

Overvoltage due to the energisation of an underground transmission cable system generally creates lower overvoltage than its OHL counterpart. No records of cable failures include the cause of failure to be an energisation overvoltage, but it is still considered relevant to conduct the studies in order to "cover the full spectrum of transient analysis" [11]. As with any other transient switching study, the initial conditions play an important role; hence, the switching instant is a key factor, determining energisation overvoltage. Circumstances such as cable length, short circuit power and X/R, cross-bonding schemes and shunt compensation affect the energisation overvoltage [11]. Unlike in OHL systems, trapped charges do not play a role due to the use of autoreclosure, but if hybrid lines employing both cable and OHL are being operated with the use of rapid autoreclosure at the OHL part, the issues of trapped charges in the cable line must be considered.

Studies have been conducted to reveal statistical switching overvoltage when energising a cable line [11]. The cumulative overvoltage distribution is depicted in Figure 10 together with the overvoltage distribution of a comparable standard OHL. The simulations were made in a Monte Carlo manner employing four different line lengths and four different equivalents in feeding networks (details are available in reference listed in {1}, {8} and {9} in [11]).

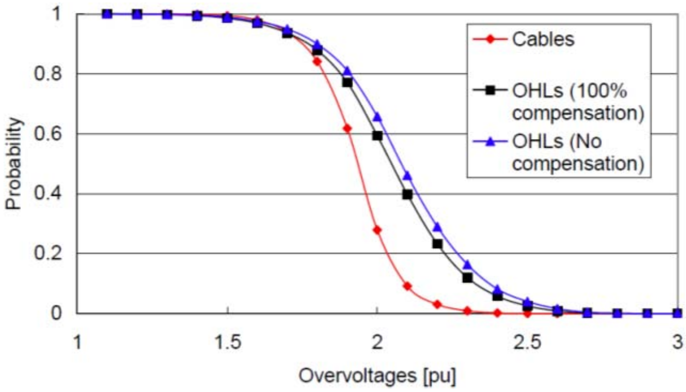

Figure 10: Probability of overvoltage versus overvoltage amplitude in p.u. for underground cables and OHL's [11].

Overvoltage for cables has a reduced probability as compared to OHL when exceeding 1.7 p.u.

The physical reason for energisation overvoltage to be smaller than compared to OHL is explained in [11], which is cited here

"• Surge impedance of cables is much smaller than that of overhead lines, because switching surge currents of the same magnitude causes lower overvoltage for cables.

• As the propagation velocity of the overvoltage is slower for cables, a cable can be considered as a longer overhead line in terms of the propagation of the overvoltage.

• In the energisation of cables, each cross-bonding point becomes the point of reflection. It is more difficult for the overvoltage to propagate to the open end terminal.

As the charging capacity of overhead lines is relatively small, there were only minor differences between overhead lines with 100% compensation and those without compensation".

Another energisation case than just "pure" energisation from in-feed network is the energisation of cables in parallel. This can take place when one substation is entirely supplied from cable lines and the "last" cable line is being energised from this substation. For instance, if a substation has three feeders, all being cables and it is supplied in some operating condition from two of the three feeders, when one takes action to energise the third and last feeder from this substation. Such energisation has similarities to the back-to-back energisation of capacitor banks in parallel. This is due to the high capacitances of the cables combined with their low series impedance; they act like capacitors when they are in a no-load condition. They are capable of generating inrush currents with large amplitude and frequency [11] and [2]. Circuit breakers (CB) are vulnerable to such high frequent inrush currents, which leads to an increased contact wear [2].

During CB closing operation, a prestrike will emerge between arcing contacts before they make mechanical contact. When switching cables in parallel, this prestrike is followed by the inrush current transient. This will give rise to a degradation of the arcing contacts, which reduces lifetime and increases the need for more regular monitoring and maintenance.

The high frequency of the inrush current displaces the current in the stationary arcing contact towards the surface due to skin effect. This leads to a wearing of the arcing contacts which is being more concentrated to the surface region of the arcing contacts than for 50 Hz currents. Hence, due to the inrush currents, the stationary arcing contact is worn to a cone-like shape by the parallel cable switching, compared to normal condition switching where contacts are worn to a hemispherical shape. The cone like wear will in time give rise to prestrikes between main contacts instead of the arcing contacts. This will damage the main contacts and lead to circuit breaker malfunction [2].

Hybrid lines are often used when a substation is located in urban areas. In order to avoid OHL in populated areas, the last kilometres of a transmission line can be laid out as a cable line, which in turn connects to GIS (Gas Insulated Substation). The transition between OHL and cable and the fact that part of the line is vulnerable to lightning makes insulation coordination studies important when connecting transformers in the GIS, especially when having open-ended busbars [11].

### *3.4 De-energisation*

Last end de-energisation of an undergrounded transmission cable system with permanently connected shunt reactors have shown to produce long lasting (several seconds) TOV (temporary overvoltage). This is the case of the initiation of the Danish underground cable research described in the introductory chapter of this thesis.

To explain the reasons of the overvoltage, the impedances in the reactors are inspected. One single phase of the system with the series impedances of the line and the losses in the reactor ignored can be considered to be the cable capacitance connected in series with the reactor inductance. The voltage across the reactor phase winding can be divided into three parts; the voltage caused by the self-inductance and the voltage caused by the mutual inductances.

This voltage before the last-end switch off can be stated with phasors with ±120° phase shift (Va, Vab, Vac), see Figure 11, which each rotate with 50Hz. The mutual couplings in the reactor are negative, shifting voltage phasors of these 180°.

In order to explain the origin of the overvoltage, we consider a case where the shunt reactor self-inductances and mutual inductances are equal (respectively) as are the cable capacitances. The disconnection is considered to occur in all phases at the same time even though we know this is not possible due to CB switch off in current zero. When the system is disconnected, the three phases will have the same resonance frequency. Therefore, the phasors, having no relative movement, will continue to rotate, and at the resonance frequency instead of 50Hz, because cable is “floating” and not connected to the network.

Under these circumstances, only one frequency will be associated with each phase and no overvoltage will occur. If the system is not completely balanced, i.e. capacitance, self- and mutual inductances are not equal in all phases, we have a different situation.

At the very moment when the system is last-end disconnected, the voltage will consist of three voltage vectors with ±120° phase shift, but gradually, when time elapses after disconnection, the phasors of each phase will start changing their individual location compared to each other and we lose the ±120° phase shift due to the slightly different resonance frequencies. This modulates the phase voltages with the modes of oscillation of the resonance frequencies. The worst case scenario occurs if both self- and mutual induced voltages align, see Figure 11.

This difference in angular frequency of the phase voltages is also the reason why small overvoltages occur when the system is balanced, but not all phases are disconnected at the same time due to CB current zero switch off. During the time between first and last phase switch off, the phases being disconnected will start oscillating with the resonance frequency while the not yet disconnected phases have the frequency equal to power frequency. This will cause the rotating phasors to rotate with different angular frequencies for this short while and thereby displacing them as compared to the initial symmetrical case [1], [11] and {7} in [10].

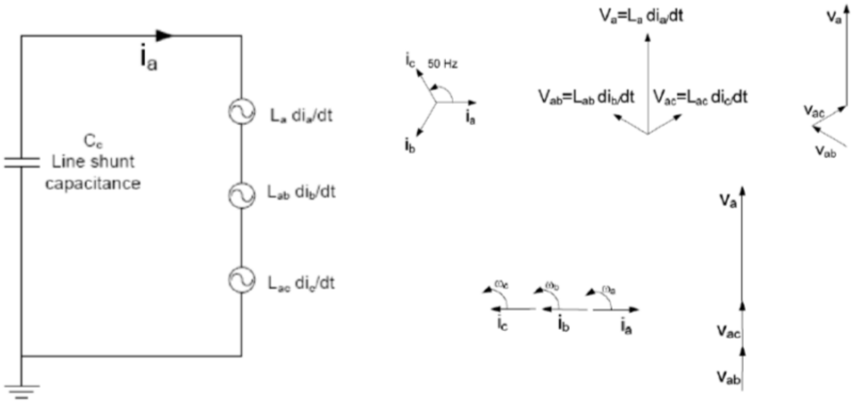

Figure 11: Single phase equivalent scheme for phase voltage (left), current and voltage phasors describing phase voltages before disconnection (right upper) and worst case currents and phase voltage composition after disconnection (right lower), {7} in [10].

The above explains the origin of the slowly decaying overvoltage when doing last-end switch-off. As can be concluded, several parameters affect the behaviour and appearance of the overvoltage (see e.g. Figure 3) such as the shunt reactor core construction and the associated self- and mutual inductance asymmetry, the asymmetry of the line inductance and, for OHL, also the asymmetry of the phase capacitances. Furthermore, the quality factor of a cable line is very high, leading to a decay taking seconds for the phase voltages to dampen out.

Further questions can be put forward when employing hybrid lines with single phase autoreclosure in the OHL part. When protective relays issues a trip command to the CB, the faulted phase is switched off in both line ends at same time and we expect voltage to lower quickly for fault arc to extinguish in order to be able to re-close with success. If the electrical arc in the faulted location can be sustained through feeding from mutually coupled sources such as the shunt reactor(s), it might not extinguish and we will experience a failed re-closure followed by a definite three-phase line switch-off. This poses a threat to power system stability and should be avoided, {8} in [10].

An analysis has been made using time domain simulations in a 400 kV hybrid line and employing a realistic arc model in order to shed light on the ability to sustain the faulted arc during single phase autoreclosure. Sensitivity studies have been employed by varying the parameters affecting this phenomenon, such as fault location, mutual couplings, arc models, arc current decay in time and network layout. The analysis ends up with the result that the ability to sustain current in the faulted location through the fault arc is not sufficient to keep the arc alive; it will extinguish, enabling the success of the single phase autoreclosure, {8} in [10]. This result is not universal as it relates to a specific Danish transmission line study case.

### *3.5 Zero-miss*

To compensate reactive power consumption of underground cables, shunt reactors SR are used. Such are used both as switchable devices located in substations as well as directly connected along the line (no CB). The directly connected shunt reactors are used mainly due to the wish of connecting the compensation at the same time as the cable itself and due to lower installation costs when not having to equip a full reactor bay with CB, disconnectors and instrument transformers.

If the directly connected shunt reactor has a degree of compensation of more than 50% of the cable reactive power generation, the current will not cross zero in the CB used to energise the cable/shunt reactor. This phenomenon has duration of several seconds. Suppose a fault happens immediately after switch on (risk of failure is higher at switch on than when the cable has been energised for a while, i.e. the first 10 seconds after switch on are more “dangerous” than any 10 second period after the cable has been energized for a few days ) the CB has to interrupt the current not crossing zero due to the zero-miss. This will lead to a lack of ability for the CB to interrupt the current and an ongoing arc will persist in the CB, which eventually will lead to an explosion of the CB.

When closing the first CB to such a cable line, cable capacitive AC current through the CB cancels with shunt reactor AC currents due to the fact that these are in complete phase opposition. At the same time, a DC current decaying exponentially will be present through the CB. This is due to the fact that current lags voltage by 90 degrees in a shunt reactor. If we connect in AC voltage zero, virtually AC current in reactor would have to be its maximum, but as a current in an inductor has to be continuous, a DC component having the same amplitude, but opposite sign must be present in order to keep current equal to zero immediately after switch on. This can be formulated as $i_L(t-) = i_L(t+)$

This leads to the maximum DC component for switching at voltage zero and no DC component for switching at voltage maximum. The DC component time constant depends of the ratio L/R for the entire system of cable and reactor, but it is usually in the range of several seconds.

Figure 12 depicts an example of two different switch-on angles and the thereby associated current through the CB, which is used to switch on the cable/shunt reactor.

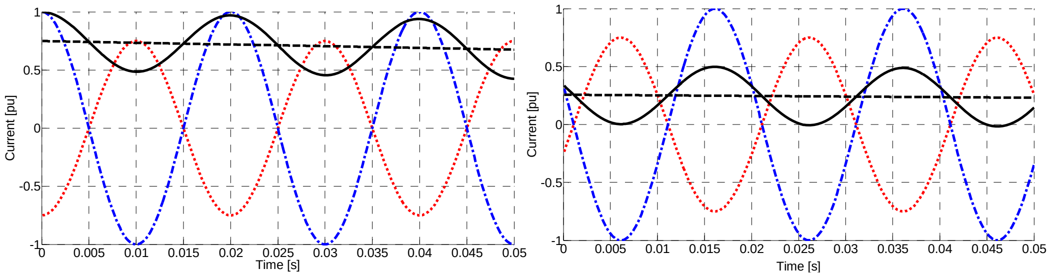

Figure 12: Current in CB during energisation for a degree of compensation equal to 75%. Dash-dot line (blue) is AC current in cable, dotted line (red) is AC current in shunt reactor, dashed line (black) is DC current in shunt reactor and solid line (black) is current through CB. Left: Switching at voltage zero 0° and right: Switching at voltage angle 70° [11].

Countermeasures must be applied to avoid the risk of switching during zero-miss. Some ways of doing this are listed below [11] and {13} in [10].

- Using SR with less than 50% compensation directly connected to the cable line
- Using pre-insertion resistors in the CB. This increases the cost of the CB.
- Synchronised switching using single-phase operated CB and point on wave equipment
- Sequential switching opening faulted phase and switching shunt reactors before healthy phases
- Energise shunt reactor after cable. Produces larger voltage steps.

The two last requires shunt reactors to have CB's, whereas this is not the case with first three countermeasures.

### *3.6 Harmonics in cable based transmission systems*

Underground cable transmission systems have much lower resonant frequency than its OHL counterparts, mainly due to the very high shunt capacitance of the cables. This leads to a shifting of the frequency characteristic resonant points towards lower frequencies which in hand leads to an increased risk of exciting resonances when switching the network. Another issue is the likelihood of a permanent resonant overvoltage or overcurrent due to transmission network background harmonic distortion. The background distortion contains harmonics, mainly due to non-linear components such as transformers (5th and 7th) and HVDC converters (LCC 11th and 13th and 23th and 25th). Furthermore, mainly due to rectifier loads, harmonic load currents from the distribution system are being transferred to the transmission network.

This increasing content of harmonics together with the reduced resonant frequency of underground cable transmission lines leads to a higher risk of harmonic excitation with the possible danger of TOV. For long lines, it even makes sense to consider the voltage magnitude versus distribution along the lines.

Figure 13 shows a realistic example of simulated frequency spectrum for different bonding configurations for a 150 kV substation having three cables with lengths of 23.7 km, 29.7 km and 47.49 km connected. All the network transformers, generators and loads are included in the model.

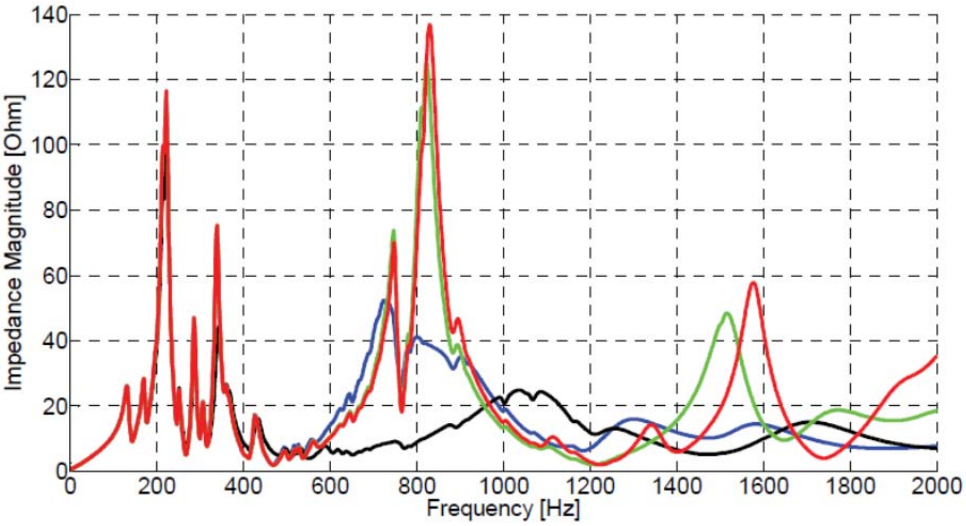

Figure 13: Frequency spectrum for different bonding configurations. Black: All cables bonded in both-ends; Blue: All cables with one cross-bonded major section; Green: The three cables attached to the reference node with three cross-bonded major sections and the remaining cables with one cross-bonded major section; Red: All cables with six cross-bonded major sections [9].

From Figure 13, it can be seen that resonances are present at low frequencies and that the bonding of the cables plays a role when exceeding around 400 Hz.

It is time consuming to assess the entire network with regards to resonances using complicated simulation studies. Therefore, theoretical formulas for estimating the frequency components have been developed as a requisite for an easier first assessment of network resonant frequency components. These are described in detail in reference {23} in [11], and the overall agreement between the accuracy of such theoretical approach and simulation studies is depicted in Figure 14.

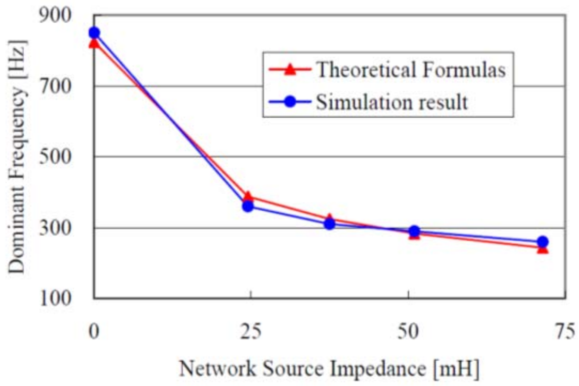

Figure 14: Comparison of dominant frequencies derived by using theoretical formulas and time domain simulations [11].

### *3.7 Modelling depth and systematic approach*

The above chapters describe the simulation studies which must be conducted when laying down the specifications for a partly or fully cable-based transmission network. Such studies are time consuming and require numerous time domain simulations. Time domain simulation runtime highly depends on the adopted model complexity, which relates to the level of detail with which the network is modelled. How detailed are the network components represented? How many components are modelled one by one or are parts of the entire network modelled by simpler equivalents?

The results obtained depend on the level of detail in the modelling approach so that the higher level of detail, the higher the accuracy, if we disregard possible numerical instabilities due to a high level of details. The dependence is so that the higher the degree of accuracy, the better should be the level of detail in modelling. However, beyond a certain level of detail, only minor improvement or no improvement of the results is achieved. Knowledge of this level of detail to reach a fair accuracy is highly valuable as it reduces computer simulation time. Such a concept is pronounced “Modelling depth” [11].

This level depends on the phenomenon under study and can be sub grouped in two categories

- Switching phenomena (3.7.1)
- Resonance phenomena (3.7.2)

### 3.7.1 Switching phenomena

Different possibilities exist for simulating the switching transient of an underground cable [11]. The cable may be connected to a lumped equivalent source which typically overestimates the overvoltage and does not give correct waveforms as it does not consider the propagation of the waves into the adjacent lines. The inclusion of the surrounding area around the node in question improves the accuracy. IEC 60071-4 suggests including only the network of same voltage level up to one or two busbars behind the node of interest, with the rest of the network being modelled by an equivalent Thévenin. Although this is a good rule, it is not accurate for all cases, mainly not when energising a long cable surrounded by shorter cables or OHLs [4] and [11].

Usually, the largest overvoltage occurs at the receiving end of the cable being energised, assuming no resonances. Typically, it corresponds to the moment when the wave generated at switching reaches the receiving end of the cable for the second time.

It is proposed [11] that the simulation model is divided into three zones, each with different levels of modelling detail. The first area includes the nodes close to the busbar of interest, it is modelled in detail using frequency-dependent models, and it contains all minor cross-sections when present. This level of detail is required because of the reflections at the end of the minor-sections and at the end of the cables/OHLs. The area contains all the lines reached in a period of time equal to τ by a wave travelling at intersheath mode speed.

The second area continues to use FD-models, but it is not necessary to include all the cross-bonded sections; it is sufficient to consider one major section. This area contains all the lines reached in a period of time equal to τ by a wave travelling at the coaxial mode speed.

The third and last area represents the cables and/or OHLs by means of lumped parameter models and it has a modelling depth of one busbar, and is then connected to an equivalent network, i.e. R-L series impedance or R-L-C pi-circuits in front of an ideal voltage source.

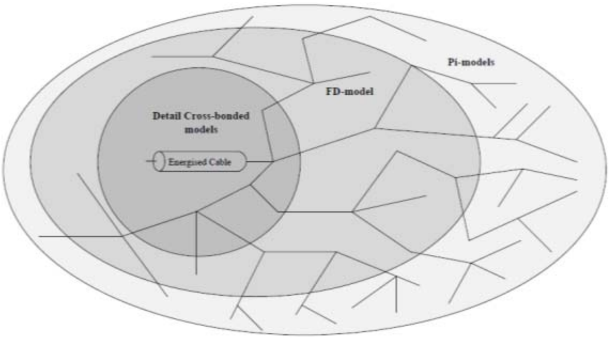

Figure 15: Three level modelling depth approach [11].

### 3.7.2 Resonance phenomena

In order to be able to calculate TOV's originating from resonances, an adequate modelling of the network is necessary. Frequency scans of the network must be available and the admittance of the equivalent network should be modelled by a Frequency-Dependent Network Equivalents (FDNE). For practical reasons, this is not normally possible, and approximations must be made using simulation models.

One possible method is to design a detailed network model and to extract the frequency domain response of the node(s) of interest and use this to obtain the FDNE. The drawback of this method is the need for a reference detailed network model.

Another possibility is to use an empirical approach consisting of (cited from [11]):

- "Designing a detailed system up to a distance of two or three busbars from the point of interest and use an equivalent network (50/60Hz) for the rest of the grid;
- Repeating the previous point, but increasing the modelling depth of the detailed area in one busbar;
- Comparing the frequency spectrums for both systems;
- Repeating the process until the difference between the spectrums is minimum around the frequencies of interest"

This procedure is somewhat time consuming and can be combined/verified with the approach of the theoretical formulas for the frequency components as described on p. 28 of this thesis.

A systematic approach is described in [4].

*Summary*

Time domain simulation tools can be used to assess the input parameters for an insulation coordination study with regards to slow front switching overvoltage in undergrounded cable systems. Harmonic resonance TOV phenomena is a severe threat to cable transmission systems and must be assessed carefully using either time domain simulation tools or an assessment based upon network frequency characteristics. The zero miss phenomena when using directly connected shunt reactors must be addressed using the countermeasures listed in section 3.5.

## 4. Protection of Underground Cable Systems

Demands for transmission power system protection are rigorous as the short circuit power levels involved are high. This is very important both with regards to system stability performance and the effects of the power dissipated in the faulted location as well as danger to humans and livestock. The tendency is that the more vulnerable the device to be protected, the more effort is put into a proper protection as is usually the case when transformers and generators are protected more efficiently than for instance an OHL. This certainly makes sense as consequences of failure are much larger for a transformer than for an OHL. The before mentioned undergoes serious damage and must undergo lengthy and costly repair [7], [8], where the OHL usually can be switched on immediately after a fault has been cleared. This feature is called rapid autoreclosure ARC and is used extensively in the transmission system, both as single phase and three phases ARC. Underground cables suffer permanent damage and need outage and repair when struck by faults. The damage can be severe and careful attention must be paid to not exceed the thermal limits of the screen which carries the single phase to ground fault current.

Therefore, a reliable and proven protection scheme employing proper main protection as well as back-up protection is of great importance for underground power cables.

Main protection of underground cable systems is usually laid out as current differential using both instantaneous value comparison and phasor comparison [6]. This is a good way to protect the cables as fibre optic communication links are laid together with the cables and can be used for the differential protection communication purpose. Furthermore, differential protection is 100% selective and fast, which is a benefit for cables in order to minimise the risk of damage during faults. It is important to set the bias current of the differential relay operating characteristic in a way insensitive to the cable charging current. Shunt reactor currents due to directly connected shunt reactors must be compensated by subtraction from cable current using current transformers at the shunt reactor.

Backup protection of cables usually uses distance protection without communication channels as a backup protection is preferably independent of communication links. In order to use distance protection correctly the measured impedance of the faulted loop must be well known to be able to lay down a setting scheme assuring both selectivity and confidence in trip when faults are present [11].

Cable faults are usually single phase to ground (SLG) faults due to the phase separation as well as the single phase screen only being separated from the phase conductor by the XLPE insulation. As seen by the distance relay, the SLG fault loop impedance is expected to be non-continuous due to the shifting of the screen currents in the cross-bonding points along the cable line [11], [3]. Distance protection relies on a linear relation between measured impedance and distance to fault. Hence, in order to be able to use distance protection for cable systems, a thorough analysis of fault loop impedance must be conducted.

An example of this is provided in [11] showing the non-continuous impedance for one major section of a proposed line in Denmark for various formations. This is shown in Figure 16.

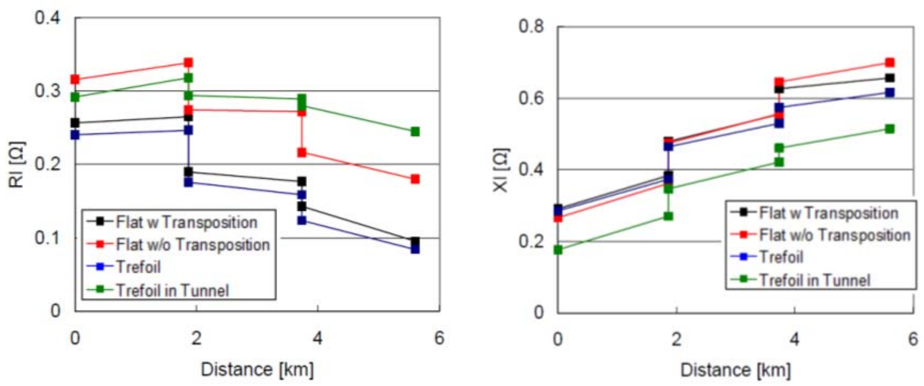

Figure 16: Real and imaginary part of impedance of one major section of a cross-bonded cable [11].

The discontinuities vary between 11% and 17%. Relatively seen, the longer the cable, the discontinuities become less and less pronounced, which in turn leads to the fact that a cross-bonded cable system can be efficiently protected by means of distance protection when the cable system's length is in the usual range for transmission lines [11], [3]. It has been analysed whether faulted current leaking to ground through a damaged cable jacket plays a role for the measured fault loop impedance. This is not the case as the screen current return path possesses much lower overall impedance than the ground return [3].

The grounding practice in substations feeding the cable line plays a role for the SLG fault loop impedance [11]. This has an influence when measuring the line impedance before commissioning the line. It can create confusion if measurements are not in agreement with cable constant calculation programs so therefore it makes sense to analyse the influence of the grounding practice upon impedance measurements.

The grounding practice can be made in two principally different ways. Either by grounding the short circuited phase conductors (for measuring the line impedance) in a location close to the grounding of the cable screen (see Figure 17 left) or by grounding the shorted phase conductor in a location far away from cable screen grounding (Figure 17 right). In the latter case, measurement current has to travel the path of the grounding system which will lead to the impedance of the grounding system to influence the impedance measurement, leading to a larger real part of the impedance as compared to a grounding of phase conductors close to screen grounding location.

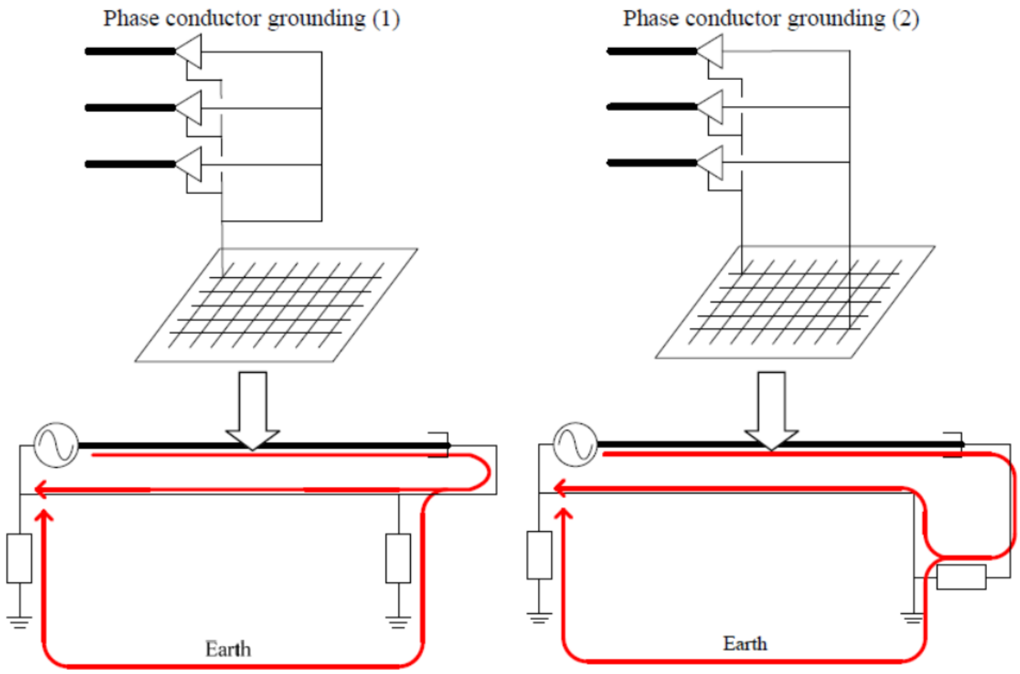

Figure 17: Influence of the phase conductor grounding location when measuring cable line impedance [11].

Measured impedance changes as given in table 1.

**Table 1: Measured impedance for different phase conductor grounding**

| Phase conductor grounding | (Figure 17 left) | (Figure 17 right) |
|---|---|---|
| $Z_1$ [Ω] | 0,487 + j5,07 | |
| $Z_0$ [Ω] | 4,82 + j2,78 | 7,50 + j3,42 |
| $K_0$ | -0,122 – j0,296 | - 0,0639 – j0,467 |

The following is cited from [11];

"The actual operation of the protection relays with regards to the dynamic behaviour of cable based transmission system, including the effects of line directly connected shunt reactors (which can be "seen" by the protection relays) and possible hybrid line configurations makes it worthwhile to study the dynamic impact on both differential and distance protection. Cable systems can be modelled in time domain simulation tools such as EMTDC/PSCAD together with relay operation  and the impact of cable system dynamics can be assessed, both with regards to trip when correct and unwanted trip. The time domain simulations can be converted into comtrade file format and used for transient replay by means of relay test set OMICRON CMC 356 advanced transplay. Thereby, real relay operation can be examined in a very realistic way."

*Summary*

Underground cable systems require premium class protection both with regards to main protection as well as backup protection as the consequences of a no-trip or prolonged time to trip might damage the cable seriously, leading to quite expensive and lengthy repair work. The use of differential protection is straightforward as long as the cable capacitive current and the shunt reactor current for directly connected shunt reactors are taken into account. Distance protection can be applied as backup protection; however, it is important to know the faulted loop impedance prior to setting the distance zones.

## 5. Fault Location in Underground Cable Systems

Usually, faults located in OHL transmission lines can easily be found by visual inspection. Furthermore, insulation of an OHL is of the self-restoring type, which means that it restores after a fault has been switched off. This is due to the nature of gaseous insulation. Conductors, armature parts, arcing devices and insulators can suffer damage due to the high temperature arc in the faulted location. Such damages are easily visible by inspection.

This is not the fact for underground cables as these are literally buried 1-2 meters below ground surface and thereby not at all visible for inspection. Furthermore, the insulation is of the non-self-restoring type, which means that a fault creates permanent damage to the cable which then must be repaired before energisation.

It is evident that the location of a fault in a cable system can be both costly, time consuming and very tedious. We need to excavate the cable in order to be able to identify the faulted location. Underground cables are often laid in farm land which means that the crops will be destroyed in case of excavation. Traditional methods of estimating the faulted location usually rely on positive sequence reactance of the line and are somewhat inaccurate, causing several kilometres of excavation of cable in order to locate the fault. Offline methods such as time domain reflectometer and bridge methods can be used to locate the fault, but it is often seen in XLPE insulation that faulted location puncture closes so the fault turns into a high resistive fault, which is difficult to locate using the abovementioned methods [11].

Methods employing re-opening of the insulation by the use of impulse currents can be used to re-open the fault, but this can either damage the cable or fail in re-opening the faulted location [11].

The repair time can be several days for an underground cable line onshore and even worse for offshore cables, where weather conditions play a major role in the ability to perform repair.

Hence, a method which locates cable transmission system faults fast and with high accuracy would be highly beneficial.

Online fault location methods can be subdivided into two categories:

- Impedance-based methods
- Travelling wave-based methods

### *5.1 Impedance-based methods*

Impedance-based fault location methods are widely used for OHL due to the continuous nature of the series impedance and the fact that larger inaccuracy means less, e.g. because a few hundred of meters of OHL can easily be overlooked. As described before, such inaccuracy is unwanted for buried cable systems. Chapter 4 has shown the discontinuous behaviour of cross-bonded cable systems, which inevitably would lead to large difficulties in accurately locating a fault. Furthermore, measuring accuracy of instrument transformers and impedance calculating device will play a major role in trying to get good fault location accuracy, or, in other words; how short a length of cable we have to excavate [11].

For hybrid lines, impedance-based fault location methods face even greater difficulties in achieving proper accuracy. This is due to the very different magnitude of cable vs. OHL impedance as well as the effect of double sided infeed [11].

### *5.2 Travelling wave-based methods*

The wave propagation velocity $v_{wave}$ is an inherently necessary parameter to be used in travelling wave fault location methods [11]. $V_{wave}$ strongly depends on the cable configuration, i.e. it depends on the cable's physical parameters and installation layout, including ECC (Earth Continuity Conductor) and soil parameters of the cable system. Field measurements must be conducted to get values for $v_{wave}$ with accuracy suitable for fault location purposes. A measurement campaign was conducted at the Anholt Offshore wind farm electrical connection and published in {38, 39 and 40} in [11], see Figure 18.

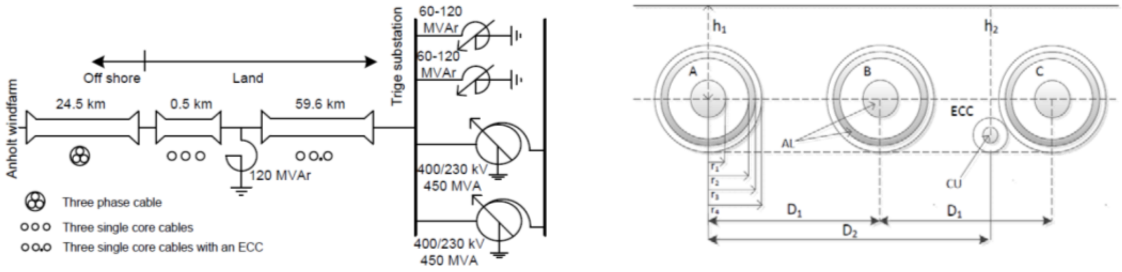

Figure 18: Anholt offshore wind power plant electrical connection [11]. Left: single line diagram, and right: the formation of the onshore 220 kV cable [11].

It is shown in [11] that the three coaxial mode velocities are equal and constant for frequencies above 10 kHz and that they are considerably faster than the intersheath and ground mode velocities.

This makes the coaxial mode velocities well suited for a travelling wave-based fault location method.

The electromagnetic pulse propagation is measured by means of a portable lightning impulse testing device and oscilloscope measuring sending end voltage and current [11].

Travelling wave fault location can be applied as either single-terminal or two-terminal methods. The single-terminal method is unsuitable for cross-bonded cable systems, as reflections from the cross-bonding point will interfere with the second wave and make it difficult to detect the reflections [11]. The two-terminal method can be stated as

$$x = \frac{l-(\tau_A-\tau_B)\cdot v_c}{2} \tag{1}$$

In (1), l is the cable length, $v_c$ is the asymptotical velocity of the coaxial mode, and $\tau_A$ and $\tau_B$ are the coaxial fault wave arrival instances at the two terminals A and B.

In [11], one example of a real-life measurement at the Anholt cable is shown in Figure 19. A fault (a short circuit) is put in a joint along the cable during the installation and the resulting waves are captured in joint 0 and 33 (sending end and receiving end).

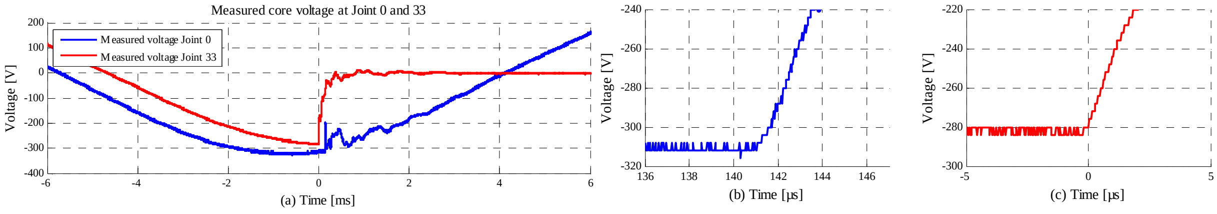

Figure 19: Measured travelling waves for two-terminal fault location purpose [11].

Using the two-terminal method of (1), the fault location can be determined with an accuracy of 30 m, corresponding to 0.08% [11].

*Summary*

Fault location in cross-bonded cable systems can be done by applying the two-terminal method. The accuracy of the latter is generally less than 100 m (i.e. faults are detected with such accuracy that distances less than 100 m needs to be excavated), which still makes it a hard task to locate faults. The two-terminal method seems to be promising for implementations in future fault locators.

## 6. Conclusions

### *6.1 Conclusions and future works in a broader perspective*

This collection of papers has presented the research progress of Department of Energy Technology and Danish TSO Energinet.dk and is undertaken in a period of ten years.

The main conclusion is that underground cable transmission systems are a technically possible way for power transmission in the future transmission network. However, compared to OHL many technical challenges are still to be faced. This requires a much larger design effort as compared to OHL design. Furthermore the operational experience with undergrounded cable systems is rather limited so it's hard to assess the major question "Are underground cables equivalent to OHL with regards to reliability and lifetime?"

The best we can do at the present is to conduct the most thorough design study when planning a new cable line. This is necessary as not much accumulated design knowledge and design guidelines have been created yet, as the cables only have been used in a relatively short time period, as compared to OHL's.

To the authors opinion the best to do is to follow dedicated design guidelines as given in Cigré Power System Technical Performance Issues Related to the Application of Long HVAC Cables, Cigré Technical brochure WG C4.502, Cigré 2013.

The work described in this publication covers many of the design studies, which are shortly highlighted in this thesis. The author has been a regular member of Cigré WG C4.502.

At the time of publication (December 2014), several papers reports a progress in both the intentions of installing underground cables, onshore and offshore as well as the actual installed systems. An example is the Cigré 2014 General session, where SC B1 holds 33 publications within isolated cables. Many obstacles have been overcome by research carried out by the research community so far, but as cable transmission systems are still in their youth, operational experience as well as continued research uncovers needs for further research in the years to come. Some key research issues are:

- Three phase submarine cables exact loss modelling
- Resonance problems in meshed transmission network employing a high share of converters
- Underground cable lifetime assessment, condition monitoring and maintenance

If underground cables become a backbone in the transmission network of the future we must expect major research effort in the years to come, probably mainly focusing in assessing and keeping the assets of the underground lines with such accuracy that reliability, lifetime and maintenance can be as easily and accurately estimated as for OHL's.

## *6.2 Main hypothesis – final remark*

The research presented in this PhD thesis and its references has led to the development of a practically useable set of tools and design guidelines enabling a widespread use of underground cables in the transmission system. The technical disciplines used to design an OHL has been reformulated and adapted to suit the design of underground transmission cable systems in order to foresee a reliable operation of such. Cable transmission is in its youth so only years of operational experience can prove the developed design guidelines to be adequate, thus leading to a long term reliability at the same level as OHL.

## *6.3 Scientific contributions*

The significance and main contributions of this PhD research project from the author's point of view can be summarized as follows:

- Identification of research needs in order to be able to design underground cable transmission systems in a reliable and practically applicable way
- Management of a 10 year research study in underground cable transmission systems
- A new OHL audible noise calculation model for snow and frosty mist
- Identification of the fundamental cause of the switching transients in underground cable systems
- Studied the wear of circuit breakers when subject to cable energisation and assessed the use of IEC 62271-100 to study this phenomenon
- A hybrid method to assess dynamic simulations studies in meshed grounding systems
- Contributions to frequency dependent underground cable model improvement and verification
- Contributions to full scale measuring methods for underground cable systems
- Contributions to simulation guidelines for harmonic studies in underground cable systems
- Contributions to analysis of the behavior of distance and differential protection application in underground cable systems
- Co-authored a book "Electromagnetic transients in power cables"
- Authored a comprehensive review paper (part 1 and part 2) giving the state of art for underground cable transmission system design studies as researched by Department of Energy Technology and Energinet.dk

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