Experience in transporting energy through subsea power cables: The case of Iceland

Svandís Hlín Karlsdóttir

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
University of Iceland
2013

Experience in transporting energy through subsea power cables: The case of Iceland

Svandís Hlín Karlsdóttir

30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Industrial Engineering

Advisors
Rúnar Unnþórsson, Lektor
Tómas Philip Rúnarsson, Professor

Faculty Representative
Magni Þór Pálsson

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, May 2013

Experience in transporting energy through subsea power cables: The case of Iceland
30 ECTS thesis submitted in partial fulfillment of a *Magister Scientiarum* degree in Industrial Engineering

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
School of Engineering and Natural Sciences
University of Iceland
Hjardarhagi 2-6
107, Reykjavik
Iceland

Telephone: 525 4000

Bibliographic information:
Svandís Hlín Karlsdóttir, 2013, *Experience in transporting energy through subsea power cables: The case of Iceland*, Master's thesis, Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, pp. 85.

Printing: Háskólaprent
Reykjavik, Iceland, June 2013

Abstract

This Master's thesis analyses the experience from subsea power cable projects in Europe to bring new aspects and gain more information and insights to this project. The main focus is on technology, reliability and environmental impact. This study of the European experience is transferred to Iceland and is evaluated as to which technology is suitable for Icelandic conditions, what to avoid and what to keep in mind, and also to evaluate the reliability of possible subsea power cables from Iceland to mainland Europe, or to Great Britain.

Útdráttur

Þetta meistaraverkefni fjallar um að afla reynslu af rekstri sæstrenga frá Evrópulöndunum hvað varðar tækni og áreiðanleika. Auk þess voru skoðaðar rannsóknir á umhverfisáhrifum þeirra. Aðstæður á íslenskum orkumarkaði voru skoðaðar og út frá samantekt á reynslu sæstrenga var metinn áreiðanleiki mögulegs sæstrengs frá Íslandi til Bretlands. Niðurstöðurnar veita mikilvægar upplýsingar um ákveðinn hluta af þessu stóra flókna kerfi sem sæstrengsverkefni er.

Table of Contents

List of Figures

List of Tables

Variable Names

AC	Alternating Current
CIGRÉ	International Council on Large Electric Systems
DC	Direct Current
EIA	Environmental Impact Assessment
EU	European Union
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
MI	Mass-Impregnated
RES	Renewable Energy Sources
ROV	Remotely Operated Vehicle
TSO	Transmission System Operator
WOW	Waiting On Weather
XLPE	Cross linked polyethylene

Acknowledgements

I would like to thank my supervisor, Rúnar Unnþórsson, for his assistance during my thesis work, Cali Nuur professor at KTH for good advice, Gunnar Gehlin at Svenska Kraftnät for information and data and, finally, my family for priceless support.

1 Introduction

The world is facing a great challenge today when developing renewable energy sources to reduce global warming and climate change. The design of an optimal energy resource mix to mitigate climate change is a challenge that many countries are facing [1, 2]. A great portion of today's energy demand is supplied from conventional energy sources (fossil fuels) such as coal, natural gas, crude oil, etc., which increase greenhouse gas emissions and may lead to global warming. Fossil fuels are finite and fast depleting which also threatens future balance of energy generation and demand [2, 3]. By increasing the geographical area for interconnection of renewable energy sources, the need for reserve capacity of power plants using fossil fuels decreases. Public awareness has encouraged sociotechnical diffusion from conventional energy sources to renewables. The benefits of renewable energy sources include a decrease in fossil fuel dependency and almost no release of gaseous emissions or waste to the environment during operation [2]. A disadvantage of renewable energy sources is their dependence on weather and climate conditions, which may lead to insufficient supply of power demand at each instant. The optimal sizing of a renewable energy system by interconnecting many sources of energy can improve the performance of power supply.

The technological breakthrough of high-voltage direct current (HVDC) transmission has made bulk electrical power transmission over long distances feasible [4]. This has made interconnected systems an interesting option for integrating electricity produced from renewable energy sources. The European Union (EU) has also set Directives [5] to cut greenhouse gas emissions by 20% from 1990 levels to be achieved by 2020, together with a 20% renewables target. The shift from fossil fuels to renewable energy sources with interconnection of autonomous power grids has started in Europe, showing an increase in renewables by 5,6% in 2010 (which is the largest percentage increase since 1973) and continuous loss of market share of oil consumption [6].

Iceland is an island situated in the North Atlantic Ocean and unlike many other places; Iceland is blessed with abundant natural source of renewable energy. In 1998, Iceland announced plans for a hydrogen economy and therefore has started the hydrogen energy transition [7], contributing to the global effort to protect the climate. Today, Iceland produces 85% of its domestic energy from renewable energy sources - hydro and geothermal [8]. Aluminium production is the major industry in Iceland, consuming 70% of total electricity generated, showing that Iceland is exporting its hydropower via aluminium metal [9].

With the knowledge from the aforementioned evolution and Iceland´s large amount of renewable energy sources, it is interesting to evaluate the possibility of transmitting electrical power from Iceland to mainland Europe through HVDC submarine power cables. This possibility has been analysed in Iceland since 1980 but has not been economically feasible until recently. Recent changes in demand for renewable energy sources, obsolescence of many coal and nuclear power plants, new technology and implementation in subsea cables and steady increase in price for electricity have made the project more economically feasible. Changes in domestic driving forces in Iceland have made this project more reliable and feasible to continue further research. The motivations are: increasing difference in electricity price between Iceland and neighbouring countries, increased security in the electricity system and access to a big electrical market. By evaluating Icelandic possibilities, Iceland could be a part of the modern clean transmission electrical grid in Europe by transporting renewable energy over to mainland Europe.

In this thesis, the experience from subsea power cable projects in Europe is analysed to bring a new aspect to this project and gain more information and insights into this possibility. As the main technical challenges for transporting electricity from Iceland to mainland Europe has been the subsea cable technology, the focus of this thesis will be on the HVDC subsea cable system, its technology and reliability. The environmental impacts from subsea power cable during installation and operation is also analysed. This study is one important part of this complex puzzle and is essential for evaluating whether the technology is suitable and economic for Icelandic conditions. It also helps evaluate if the benefits for implementing and operating such a large complex technical system are acceptable for interested parties in Iceland and will provide a reliable supply of electricity to meet the needs of the customers.

1.1 Motivation and objectives

The experience of electrical transportation through subsea power cables in Europe will be analysed. The summary will provide greater understanding in evaluating how reliable subsea cable systems are and what technology is suitable for such transportation. Those results will be used for the case of Iceland. The objectives are to answer the following questions:

- What type of technology is suitable for bulk electrical transportation through subsea power cable over long distances?
- How reliable are subsea power cables? That is, how many hours of the year does a subsea power cable transmit electrical power? What is the average down time, where no electricity is transmitted and what is the extreme case?
- What are the environmental impacts from subsea power cable systems during installation and operation?
- Based on the experience collected in this work, what can be expected for Icelandic conditions and transportation of electricity through subsea power cable from Iceland to Britain?

This thesis work is built on documentation review, such as journal articles, books, published reports and researches, theoretical and empirical. The work includes both quantitative and qualitative gathering. Interviews with specialists in the field where carried out and evaluated and summarized in context to the thesis objectives.

1.2 Contributions

The main contributions of this work to the body of scientific knowledge are that the suitable technology is high-voltage direct current transportation and there are two dominant cable types for long distance transportation. Mass-impregnated cables and extruded XLPE cables, they carry 500 kV and 320 kV, respectively.

The subsea cables system reliability, or the percentage of how many hours of the year it transports electricity to load destination, is dependent on failure statistics and outage duration. That is, it is dependent on how often failures occur per year and how long time it takes to repair the cable system; the repair time is then dependent on the time the repair vessel has to wait for acceptable weather to do the repair work. The main causes for subsea power cable damages are fishing activities and anchors. The failure rate for high-voltage direct current mass-impregnated cable system is on average 0,1 failure/year/100cckm and the average outage duration for the North Sea is 54 days. Shortest repair time is within two weeks while the longest repair time can reach 4 months on the North Sea. The reliability changes significantly with cable length, fault location and weather conditions.

The environmental impacts are negligible during installation and operation. The experience shows that the impact on sea bottom sediment during laying of the subsea power cable will recover after approximately one year. There are no electric fields and the magnetic fields are eliminated by laying two cables in close proximity. In the best cases, the magnetic field is only measured in a two-metre radius from the cables. The heat released from the cables during operation heats up the closest environment but that affect decreases with distance from the cable. There is no evidence in literature that the magnetic fields do harm to marine life or surrounding environment.

For the case of Iceland the estimated length of the cable is 1.170 km and will lay from the East coast of Iceland, pass Faroe Islands and connect at north coast of Great Britain. The maximum depth will reach 1.200 m. The suitable technology is high-voltage direct current mass-impregnated cable with double layer armouring to withstand tensional forces during laying. The cable is supposed to be protected from fishing activities and anchors by being buried at least 2 m under the sea bottom. The reliability of the cable from Iceland to Great Britain changes with different fault locations and between seasons. With fault location approximately 400 km offshore the Icelandic coast it is estimated that no repair work can be done during winter (Nov. – Feb). The reliability for single cable subsea system from Iceland to North coast of Great Britain is estimated 74%. That is on average there will no electricity be transmitted for 1.939 hours a year.

1.3 Structure of the thesis

In the next chapter, Chapter 2, the electric power system is described, how it works and its evolution in Europe. The chapter starts with a description of the fundamentals of electric power in order to provide necessary information to understand the system as a whole. Then submarine cable systems are described, i.e. the cable types, structure and properties. Chapter 3 continues with a description of the development of high-voltage direct current (HVDC) systems. The chapter also provides a study of the technical development of HVDC submarine power cables. Chapter 4 provides information on reliability, utilization and failure statistics of submarine power cable systems. Chapter 4 also provides an overview on factors that can possibly increase reliability and extend the cable lifetime. An overview of the environmental impacts from installing and operating submarine cables is provided in Chapter 5. Chapter 6 provides a case study of Iceland. It describes the available energy sources, the electrical transmission system and the experience of using submarine power cables in Iceland. A discussion and summary of the Icelandic case study and recommendations for further work are provided in Chapter 7.

2 Electric Power Systems

Electric power systems consist of generation, transmission and distribution. Electric power systems are large complex systems that undergo various reconfigurations. Those changes might seem to be a revolution but can be the outcome of a small series of adaptations over time. In the early days, the electric power systems were regional and served energy supply to local cities. As the electrical utility increased and the requirements for energy security rose electric power systems became interconnected. The electric power systems developed into electrical grids, an interconnected network for high voltage electricity transmission from generation to load destination. Regional systems transformed to national and national into transnational ones. Another reconfiguration were the reorganizing of previously monopoly systems into new configurations based on principles of competition and open access as the European electricity grid was reshaped. Large integrated markets enhance productivity, improve efficiency and increase security of power supply.

The process of transmitting electricity through the electric power system is as follows. Electricity is generated in power plants and then transformed to high-voltage (HV) electrical energy for transmission to the distribution substation. The electrical energy is then stepped down to a lower-voltage for a distribution to the end user. Electric power systems are real-time electrical energy delivery systems. Real time means that power is generated, transported and supplied the moment you turn on the light switch. There is no excess electricity generated, what is produced is consumed. Those systems are not storage systems like water systems and gas systems [10, 11]. Producers need to provide generation capacity to satisfy all individual demands and fluctuations, or electrical load. Electrical load is the power consumption in the electrical circuit and peak load is historically high consumer demand for a certain period. The demand is estimated daily, 24 hours a day and the generation is set in accordance to the demand estimation. When the demand is estimated low, generators are slowed down. When demand is estimated higher, the generators are accelerated and more electricity produced. Figure 2.1 shows a simplified model of electrical power system.

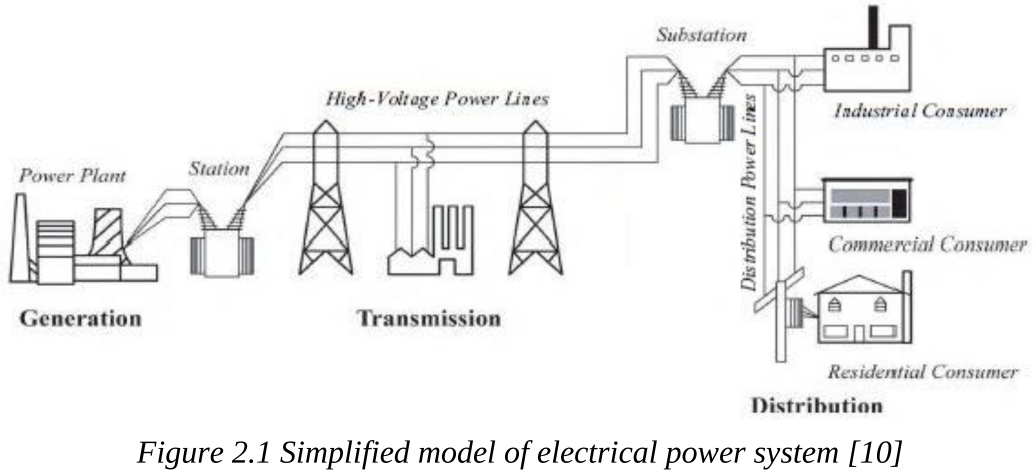

Figure 2.1 Simplified model of electrical power system [10]

Interconnected power systems, or power grids, are distribution systems with multiple available power sources in the form of power plants, which can loop throughout the network. If one source goes down, a different source can be activated to maintain service. As mentioned earlier generation must be balance against power demand. A few percent difference [11] between generation and demand influences service quality which may lead to the damage of generators or customer equipment, brownouts, or even to local or more widespread blackouts. Interconnected power system [11] increases efficiency and security. It also affects the transmission lines as they become efficiently used with more load on average, transmission service has a higher quality and is more reliable. Economically, the cheapest energy can be used first and the most expensive for peak loads. Power grids offer many important advantages over the alternative of independent power islands.

The quality, efficiency and security of the electric power system is highly dependent on the technology in use and its development. In such a highly complex system there are many different subsystems with distinctive technology. As for Icelandic conditions, the main technological challenges are the length and depth of the cable route. The focus in this thesis will be on subsea cable system technology and reliability. This chapter starts off with an overall description of the European electricity grid to gain insights into the major participants, the fundamentals of electrical power and the high voltage system. A more detailed description is made for the subsea cable system. Those topics are to ensure a basic knowledge of the different elements that make up a cable system.

2.1 European electricity grid

An electrical grid is an interconnected network for high voltage electricity transmission from generation to load destination. Transmission system operators (TSOs) are responsible for the bulk transmission of electric power on the main high voltage electric network. In Europe they interconnect through ENTSO-E [12] which is the European network of transmission system operators for electricity. ENTSOE has been functional since July 2009 and represents all electric TSOs in the EU and others connected to the network, for all regions, and all their technical and market issues. ENTSOE´s main objectives are secure energy supply, to facilitate integration, enhance relevant R&D for acceptable transmission infrastructure and consultation with stakeholders and energy policy issues. There are 41 TSOs from 34 countries that are members of ENTSOE. The TSO in e.g. Sweden is Svenska kraftnät (the Swedish national grid), in Denmark it is Energinet.dk, in Norway it is Stattnet, Nederlands the TenneT NL, Italy Terna and in the UK there are four TSO´s, National Grid, SONI, SHETL and SP Transmission.

Nord Pool Spot [13] runs the leading power market in Europe with 370 companies from 20 countries trading on the market. In 2012 Nord Pool Spot had a turnover of 432 TWh, including the auction volume in the UK market N2EX. Nord Pool Spot AS is owned by the transmission system operators Stattnet SF, Svenska Kraftnät, Fringrid Oyj, Energinet.dk and the Baltic TSOs Elering and Litgrid. The power price is determined by the balance of demand and supply and can fluctuate with weather conditions and power plant production capability. That arrangement makes it easier to identify where there is a shortage in electrical capacity, where the price is quite high. The power market has an energy mix of hydro, thermal, nuclear, wind and solar power which makes it more “liquid” and increases the electrical security, or secures the power supply. The Nordic countries deregulated their power markets in the 1990s and the Baltic countries (Estonia and Lithuania) in the late 2000s. Deregulation means that the state is no longer running the power market, instead there is free competition. It was done to build large integrated markets as they enhance productivity, improve efficiency and increase security of power supply.

2.2 Electric power

The transportation technology relies among other things on whether the electrical current is alternating or direct. Therefore it is important to begin by reviewing the difference of those two types of electrical current and to dig a little into the basics of electrical physics. That should expand the knowledge adequately to be capable of evaluating if the technology is available for the case of this project.

The physical laws for generating electricity [10] are Faraday´s law which states that "a voltage is produced on any conductor (wire) in a changing magnetic field" and Ampere´s and Lenz´s law states that "a current flowing in a wire produces a magnetic field around a wire". The combination of those two physical laws makes our power systems work. They are used throughout the entire electric power system from generation through transmission, distribution and consumption.

Those laws set the Equation 2-1where voltage times current is power and the power is used to produce real work. Electric power is the rate of flow of energy past a given point of the circuit.

$$P = V \times \mathrm{I} \qquad \text{2-1}$$

$$watts\ (W) = volts(V)\ \times amps(I) \qquad \text{2-2}$$

Equation 2-1 shows the relationship between voltage (V) and current (I) without any losses. The outcome is power (W). By raising the voltage the current reduces for the same amount of power. Equation 2-2 shows the units of Equation 2-1.

The power losses in conductors (wires) are calculated by the formula

$$Power\ Losses = I^2 R \qquad \text{2-3}$$

Also called the "Ohmic losses" where I is the current and R is the conductor resistance. The formula states that less current results in less power losses.

The electric resistance is a really important property of the conductor and is dependent on the ambient temperature and is calculated as shown below:

$$R_\theta = R_{20} \cdot (1 + \alpha(\theta - 20)) \qquad \text{2-4}$$

The conductor is either copper or aluminium and R_θ is specific resistivity at temperature θ (ºC), R_{20} is specific resistivity at 20ºC and α is temperature coefficient of the electric resistivity. Electrical energy is the product of electrical power and time. The amount of time (*t*) a load is on (current is flowing) times the amount of power used by the load (*W*) is energy [10].

The measurement for electrical energy is watt-hours (*Wh*), see Equation 2-5.

$$Wh = W \times t \tag{2-5}$$

There are two types of currents that can be produced, alternating current (AC) and direct current (DC). Their differences are described in the next chapter and their suitability for bulk electrical power transportation over long distances is evaluated.

2.2.1 AC voltage and current

AC current is produced in power plants where the generators use magnets in such a way as to produce AC current, single-phase or three-phase, (one to three coils of wire) in the presence of a moving magnetic field. Most power plants use three-phase AC current for steady power [10].

AC current flows in one direction for a period of time and then switches direction, going the opposite way. It switches direction over and over again continuously. Figure 2.2 shows the voltage increasing and decreasing, completing one cycle. This describes a sine wave in mathematical terms. The sine wave can repeat many times in e.g. a second, the time it takes to complete one cycle in a second is called the period of the cycle.

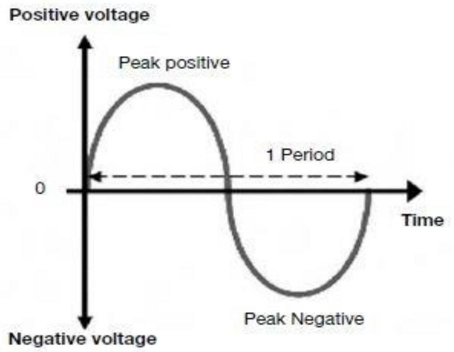

Figure 2.2 Alternating voltage [10]

In Europe the AC current in power lines switches direction, forward to backward, then backward to forward, 50 times each second. This is a frequency of 50 Hertz and is 50Hz AC electricity. The U.S. uses 60Hz AC electricity. It is also relatively easy to change the voltage of the power in AC transmission lines using transformers.

A transformer is a device that changes the voltage in alternating voltage (AC) electrical circuits. It comes in all shapes and sizes. A simple transformer has two sets of wires wound around it for input and output voltage, see Figure 2.3. The current flowing in the coil on one side (primary winding) generates a voltage in the coil on the other side (secondary winding). The windings are usually wound around an iron core as it increases the efficiency by strengthening the magnetic field and reduces transformer losses.

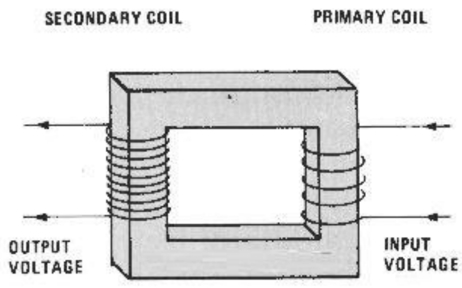

Figure 2.3 Simplified AC transformer

The power coming into a system is equal to the power going out of the system; the power is equal on both sides.

$$V_i \times I_i = V_O \times I_O \qquad 2\text{-}6$$

Where I_0 is the output current, I_i is the input current, V_0 is the output AC voltage, V_i is the input AC voltage

The voltage output of the transformer has the following relations:

$$V_0 = V_i(N_0/N_i) \qquad 2\text{-}7$$

Where N_0 is the number of turns in the secondary coil and N_i is the number of turns in the primary coil. The turn ratio is given as:

$$N_i : N_0 \qquad 2\text{-}8$$

If a simple AC transformer has the turn ratio 2:1 and has 240 Vac at 1 amp applied on its primary windings, it will produce 120 Vac at 2 amps on its secondary winding. Raising the voltage lowers the current which results in drastically lower system losses, as mentioned earlier.

2.2.2 DC voltage and current

DC current is produced by solar cells, fuel cells and transformed from AC to DC current. A battery produces DC current when connected to a circuit. DC current always flows in the same direction from starting point to end destination. The voltage can vary but is always with the same sign, indicating that it always goes in the same direction. Therefore DC voltage could not be changed with the configuration of the transformer. DC transformers have been developed but AC transformers scored over DC when electricity was first used around the world which makes it hard to convert to a DC system [10, 14].

2.2.3 HVAC vs. HVDC

For both AC and DC power it is much more efficient to transmit bulk power over long distance through high-voltage transmission lines than through lower-voltage lines [10]. Taking advantage of the power Equation (Equation 2-1), where power equals voltage times current, increased voltage results in lower current. Less current gives less transport losses (Equation 2-3) and smaller conductor sizes [10]. High-voltage transmission structures are larger and require wider right of ways (ROW). ROW is the land that is used under the structure to transport the energy and the road for easement of maintenance. However, higher-voltage structures can require less right of way land than multiple lower-voltage lines that are side by side. It is therefore cheaper than the continuous cost of high losses in lower-voltage power lines [10]. The difference can be seen in Figure 2.4.

Evaluating transmission cost in AC and DC lines, DC line can carry as much power with two conductors as an AC line with three conductor of the same size, assuming similar insulation requirements for peak voltage level. A DC line requires smaller ROW than an AC line and simpler and cheaper towers. That reduces conductor and insulator costs. Therefore the capital costs of an HVDC transmission line are less than an equivalent HVAC line with the same transmission medium and capacity [4, 14].

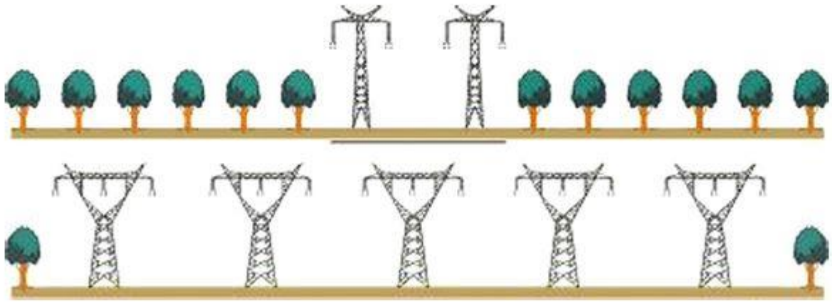

Figure 2.4 ROW size difference for HVDC (above) and HVAC (below). 1060 km, 2x3000 MW, 500 kV. [4]

The power transmission losses are also reduced in DC lines to about two-thirds of a comparable AC system [14]. High-voltage alternating current (HVAC) transmission losses may increase with distance, whereas HVDC losses are relatively constant [4]. However HVDC transmission systems also require converter stations that are more costly than the sum of their equivalent AC substation components. This introduces the concept of a “break-even distance” related to the cost differentials between technically equivalent AC and DC transmission links. AC is more economical for distances less than the “break-even distance” but is more expensive for longer distances. At present the “break-even distance” is quoted at around 500-800 km for landlines, depending on the size of the project, but may be as low as 50 km for the replacement of subsea cable system, see Figure 2.5 [4, 14].

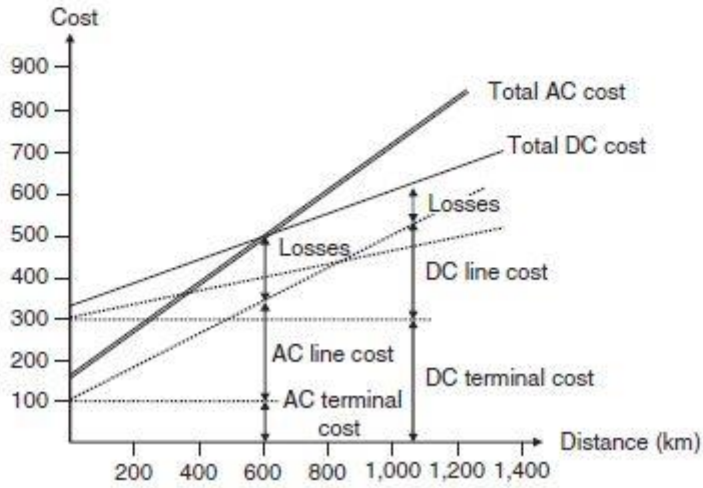

Figure 2.5 Cost as a function of line length for equivalent capacity of HVAC and HVDC transmission lines [4]

The "break-even distance" is being effectively decreased with reduced costs of new compact converter stations.

Evaluating technical issues of AC and DC transmission systems, DC power overcomes some of the problems associated with AC transmission. Those problems are limitation due to system stability limits, complications in voltage control, line compensation, problems of AC interconnections and ground impedance

Stability limits in an AC system is related to its angular difference between the voltage phasors at the two line ends as the angle increases with distance. The power carrying capability is therefore affected by the distance of transmission; the angle is inversely proportional to the transmission distance. For DC lines the power capability is unaffected by the distance as it may be independent of phase relationships [4, 14]. The complication in voltage control in AC circuit is the maintenance of constant voltage. The voltage profile is relatively flat for a constant power transfer but varies with the line loading. With increased line loading and line length reactive power requirements increase. DC power flow controllability, on the other hand, may be pre-determined which prevents the unintended overloading and under-utilization that may occur in AC systems. Those problems in AC cables make the breakeven distance for cable transmission around 50 km. Faults and oscillations do not transfer across HVDC interconnected systems which minimizes system disturbance. To overcome the stability limitations and line charging, line compensators are necessary. Line compensators increase power transfer and voltage control in AC lines while they are not needed in DC lines. The interconnections of AC ties can be problematic where large power oscillations can lead to frequent tripping, it results in an increase in fault levels and transmission disturbances from one system to another. The controllability in DC lines eliminates all of those problems. The asynchronous interconnection of two power systems can only be achieved with a HVCD link which improves the stability. The ground impedance is negligible for DC current while it has a big impact on AC transmission and can result in telephonic interference. For a single-core concept (mono-polar) one conductor with ground return is used [4, 14].

The main limitation of DC transmission is the inability to use transformers to alter voltage level. Other disadvantages have been overcome with the latest developments such as thyristor valves. Those improvements have resulted in improved reliability and reduction of conversion costs in DC systems [14].

The applications for HVDC transmission may be divided into four categories. Underground or underwater cables where there are long cable connections over the break-even distance of about 40-50 km. Long distance bulk power transmission where it is more economical when the distance is over the break-even distance. One application is asynchronous interconnection of AC systems and another is for the stabilization of power flows in an integrated power system.

Most power grids use AC lines which indicates that DC transmission is justified only for specific applications. It is unlikely that AC grids will be replaced by DC power grids in the future as the latest developments in DC structure is complex and the inability of voltage transformation in DC networks imposes economic penalties.

2.3 HVDC systems

Because of the aforementioned advantages of HVDC transportation that technology is evaluated as most suitable for bulk transportation through subsea power cables over long distances and is described in the contribution to this work in Chapter 1.1. The focus will therefore be on HVDC transportation. The main process of the HVDC system is the conversion of AC current to DC current at the transmitting end (rectifier) and vice versa at the receiving end (inverter) as seen in Figure 2.6. HVDC system transmits power from a generation source to load destination.

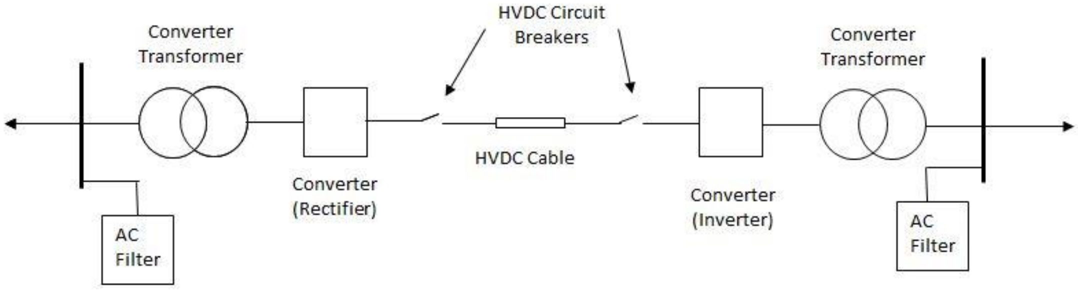

Figure 2.6 HVDC scheme

HVDC solutions have become more attractive for today´s long distance electrical transmission as it has environmental advantages, is economical as it is the cheapest solution, allows asynchronous interconnections, and has power flow control combined with the added benefits to transmission such as stability, power quality and other things.

2.3.1 Configurations

There are three main configurations [4, 14] of the HVDC system:

- Mono-polar system
- Bi-polar system
- Back-to-Back (BB or B2B) system

A mono-polar system has one HV cable and a return conductor to complete the circuit. The return conductor is either ground or sea-return or through metallic conductor. Metallic conductor is used where there are concerns for harmonic interference or corrosion exists or where undesirable DC magnetic field interactions may occur.

A bi-polar system uses two HV phases, one positive polarity and the other negative polarity, in relation to the ground. Bi-polar systems consist of two mono-polar systems. The two conductors may be two single-core cables laid separately, they may be bundled together or armoured together. Normally the current in both poles are equal with almost zero ground current. A bi-polar system has improved system availability as each system can operate independently with a ground return, then one pole can be arranged to continue to transmit power while the other is out of function for e.g. maintenance or repair.

Back-to-back systems are usually used to connect two AC systems operating at different frequencies and to improve system stability. Therefore it normally has lower DC power ratings than other schemes. The AC systems are located close to each other and may be synchronous or asynchronous.

The AC/DC conversion is achieved [4, 14] through current source or voltage source schemes where there are current source converters or voltage source converters. In a current source converter the DC current always flows in one direction while in a voltage source converter the voltage has a constant polarity.

One example of current source converters is the capacitor commutated converters (CCC) which are characterised by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves.

One example of voltage source converters is VSC (voltage source converter) where the valves are built up with semiconductors with the ability to turn-on and turn-off. The semiconductors are known as gate turn-off (GTO) thyristors, insulated gate bipolar transistors (IGBTs), and insulated gate commutated thyristors (IGCTs). IGBT and GTO have both been in frequent use in industrial applications. The VSC does not require an external source of reactive power for reliable commutation and it can therefore be used to feed weak or isolated power systems where little or no generation exists. VSC schemes allow for independent control of the magnitude and phase angle of the AC side voltage which offers the possibility to control both active and reactive power independently. This makes the voltage source converter a close to ideal component in the transmission network.

The main elements of the HVDC system [4, 14] are: the converter stations at the transferring and receiving ends, the transmission medium and the electrodes.

2.3.2 Converter station

Converter stations consist of valves, transformers and filters and are described below [4, 10, 15].

Thyristor valves are a controllable semiconductor that can carry very high currents and is able to block very high voltages. When the thyristor valves are connected in series it is possible to build up a thyristor valve which can operate at very high voltages. They can be built up in different ways, depending on application and manufacturer.

Insulated gate bipolar transistor (IGBT) devices are now used in VSC schemes with lower voltage and power rating than thyristor valves. As mentioned above it has the advantage of a turn-off capability but the disadvantage is higher conduction losses.

The converter transformers adapt the AC voltage level to the DC voltage level and they contribute to the commutation reactance. They may consist of the following arrangements, i) three phase, two winding, ii) single-phase, three-winding and iii) single-phase, two-winding. Star and delta connections are used for neutral point ungrounded. They must withstand DC voltage stresses and low order harmonics.

AC filters are installed to lower impedance and limit the amount of harmonic to the level required in the network. HVDC converters create harmonics in all operational modes. Those harmonics can create disturbances in telecommunication systems. Both tuned and damped filters arrangements are utilised.

DC filters are used to filter DC harmonics. There are both damped and active filter arrangements available. Active filters are a modern practice and are increasingly utilised for efficiency and space saving purposes as they are relatively small. There is no need for filters in pure cable transmission and Back-to-Back HVDC stations. It is however essential to install DC filters if an overhead (OH) line is used.

The transmission medium, or the cable system, is also essential part of the HVDC system and will be described in the next chapter.

2.4 HVDC cable system

The HVDC cable systems are both adequate for onshore and offshore applications. For bulk transmission over land overhead lines (OH) are used. They are usually bipolar i.e. two conductors with different polarity.

Subsea cables are used in underwater HVDC applications and they have been manufactured, developed and implemented for over a hundred years. The main applications are power supply to marine platforms, transportation to and from islands and offshore wind farms and a connection of autonomous electric grids.

The manufacturers and design of the subsea cables are of great variety, all made with contemporary engineering skill and entrepreneurship. This chapter focuses on different cable types, cable properties and cable structures that are currently being produced and installed. It describes the cable properties and different subsea cables and their construction elements without going too deep into formulae.

2.4.1 Cable types

The following are the main types of power cables, they are usually categorised on the basis of their insulation system [16-19]. They are:

Polymeric

- Low density polyethylene (LDPE)
- High density polyethylene (HDPE)
- Cross linked polyethylene (XLPE)
- Ethylene propylene rubber (EPR)

XLPE cables have not been suitable for HVDC transmission because of the space charges in the insulation. Space charges accumulate in certain places in the insulation wall and create uncontrolled local high electric fields causing dielectric breakdowns. Another reason has been uneven stress distribution due to temperature dependent resistivity causing overstress in the outer part of the insulation.

XLPE cable types are the first choice for HVAC transportation and are available for voltage rate up to 500 kV for land cables. XLPE subsea power cables are available for > 50 km length up to 170 kV

Extruded

Extrusion makes the cable surface extremely smooth against the insulation. Extruded cables are e.g. XLPE insulated. Extruded XLPE cables have overcome the disadvantages with the XLPE cables and are suitable for HVDC transportation for up to 320 kV for a single cable power of 500 MW.

Fluid filled (FF or LPOF)

Self-contained fluid filled cables are paper or paper propylene laminate (PPL) insulated with an individual metal sheath and impregnated with low pressure oil. The necessary pressure in subsea oil-filled cables is maintained from pressure feeding units on the shore station. Maximum lengths of the oil-filled cables are approximately 30-60 km. For longer length a sufficient oil flow cannot be guaranteed.

Mass-impregnated (MI or solid)

Paper insulated with individual metal sheaths and impregnated with a low viscosity polybutene compound. This cable type has been used for bulk DC electrical transportation over long distances at high voltages. They are available for up to 500 kV and single cable can carry 800 MW. This cable type can be used for virtually infinite length because they have such high-viscosity compounds and are not dependant on pressurization from on-shore feeding stations.

Comparing those cable types the most suitable cables for bulk HVDC transportation over long distances are extruded XLPE cables and mass-impregnated cables which are described in the contribution to this work in Chapter 1.1. They transmit HVDC power with capacity up to 800 MW and voltage rating between 320 kV and 500 kV. Neither cable is limited by their length. Other cables are only suitable for HVAC transportation and limited by the length, power or voltage rate. They therefore do not fulfil all requirements.

2.4.2 Cable structure

The main layers of the subsea cables are shown in Figure 2.7 and are [16, 17, 19]:

- The conductor (wire)
- Insulation
- The water-blocking sheath
- Armouring
- Outer Serving

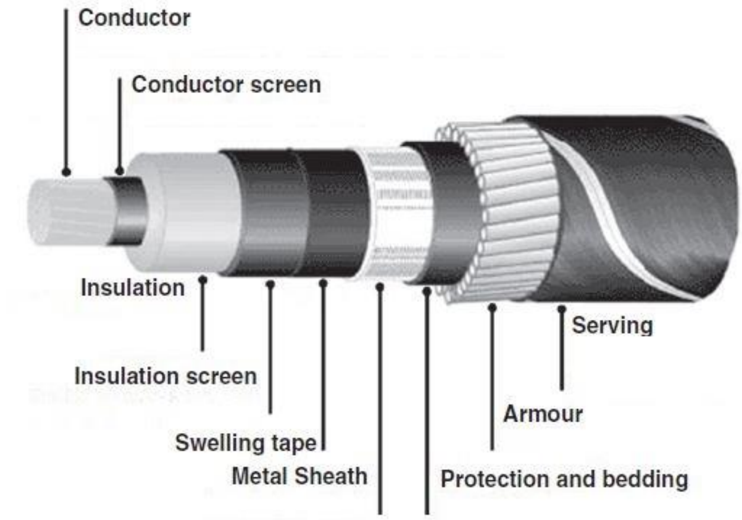

Figure 2.7 Subsea cable [19]

Conductor

The conductor is normally made from either aluminium or copper. Copper has lower resistance and thus a higher power capacity. Copper is heavier and more expensive but also has a smaller cross section and therefore requires less material for the outer layers. Aluminium is subject to limited corrosion.

There are several types of cables; it can be solid, stranded from round wires, profiled wire, and hollow for oil-filled cables. Solid cable is limited by its cross section of 400 mm^2 and the voltage rate of 150 kV. Stranded cables from round wires have lower conductivity compared to other types. Profiled wires can have a large cross section and transmission power. Hollow wires contain a central duct in the conductor to allow for oil flow in connection with thermal expansion and pressure supply from the cable terminations.

Insulation system

The insulation is placed around the conductor and prevents current from passing through it. The insulation is required to be clean and even, have high dielectric strength, and be temperature and ageing resistant. The main insulation materials are impregnated paper and polymer.

Mass impregnated non draining insulation is impregnated with a low viscosity polybutene compound which can then be used for an indefinite route length as it is not dependant on external pressurization from on-shore feeding stations. They have a smooth surface which reduces voids and strengthens the cable.

Oil filled paper insulations are used to overcome the effect of voids and minimize the losses at high voltage rates. In oil filled cables, the formation of voids is prevented by maintaining a flow of oil under pressure. The impregnation improves the dielectric properties.

In polymer insulation the insulating XLPE compounds must act as thermoplastic materials, be immune to thermal degradation and must not be prone to defects such as voids, protrusion and contaminants. XLPE is cross-linked polyethylene. Compared to paper insulation systems, polymers have no risk of leakage or fire, are simple in design and have lower dielectric losses [17, 19].

Extrusion makes the cable surface extremely smooth against the insulation which is done to avoid local stress and which increases the strength of the insulation. They have XLPE insulation.

Sheath

The water-blocking sheath is used to maintain the dielectric strength of the insulation to provide protection against water. Most high-voltage subsea cables have a metallic sheath, made of aluminium, lead, copper, or other metals.

Armouring

The armouring provides both tension stability and mechanical protection. It should be designed to withstand installation forces and provide enough mechanical protection against external aggression by installation tools, fishing gear, and anchors. The armouring is composed of wires wound around the cable usually with a diameter of 2-8 mm.

Outer serving

The outer serving protects the armouring from corrosion during loading, laying and burying processes of the subsea cable. The outer serving is either extruded polymer or made from wound yarn layers.

Cable joints

The joints connect cable parts along the cable route to form one cable. The joints are supposed to withstand all the same electrical, thermal and mechanical properties as the cable. The joints come in different shapes, such as factory joints, installation joints, repair joints, flexible and stiff joints.

The installation joints describe a joint of the complete cable including all of its layers; while factory joints do not include the armouring layer. Flexible joints are used for long cable routes requiring offshore jointing. Stiff joints have a rigid outer casing which serves as a connecting point for the cable armouring wires of each cable end.

2.4.3 HVDC cable properties

The HVDC cable properties are essential to recognise in order to achieve the required performance at a reasonable weight. It is also important to assess applied forces and stresses on the cable during installation and operation as they impact the cable properties, and therefore the power capability and the reliability of the cable. The limitation on the power capacity of HVDC power cables are mainly due to the insulation thermal constraints. The optimum power is a function of the thickness of the insulation and material properties [20]. The armouring material decides the tensional and mechanical strength of the cable which makes it important to identify material properties and likely external violence.

Thermal properties

The thermal properties of the power cable are used to calculate the conductor size needed and insulation thickness. The conductor is supposed to transport a certain amount of power without exceeding the thermal limitations of the cable material or the environment. During use a load heat is generated in the conductor which is transported outside the cable and into the ambient. The ambient is the surroundings of the cable and can be e.g., air, sea or soil thermal characteristics. The heat generated is the ohmic losses, which are the only heat source in the HVDC cable. The heat is transmitted to the insulation and creates electric stress distribution in the cable insulation, which is a strong function of the cable insulation resistivity. The electric stress distribution reaches a critical limit at a certain voltage making failure of cable insulation unavoidable. The steady-state maximum temperature in the cable insulation needs to be kept less than or equal to the maximum operable temperature, which is typically 50% of the decomposition temperature of the insulation material [20-22]. With changes in the load the temperature and pressure changes which affects the cable material and therefore the electrical properties. With higher voltage level the ohmic losses become smaller, reducing the thermal power available.

The environmental conditions in the immediate vicinity, the ambient, of the cable also influence the thermal breakdown of the cable insulation. With higher ambient temperature there is an increase in temperature difference between the conductor and the ambient causing a larger temperature drop over the insulation resulting in a lower thermal breakdown voltage. Therefore decreasing the maximum power capacity [20-22].

The ohmic losses of the conductor are therefore dependent on the conductor resistance and ambient temperature. There are lower losses with lower resistance in the conductor and the losses also reduce with lower ambient temperature [20-22].

Cables buried in the sea floor use the benefits of the thermal capacitance of the surrounding soil. Cables that are laid on the seafloor cannot use those benefits and the surface temperature of those cables follows the seafloor temperature. They have no thermal reserve from the ambient soil and therefore offer very little overload capabilities [21].

To increase the reliability of the cable a thorough submarine route survey needs to be done. Good knowledge of the thermal surroundings is critical as the avoidance of hot-spots.

Precise knowledge of those parameters can save investment cost and increase the availability and the lifetime of the cable.

Mechanical properties

The mechanical limitations of the cable are essential to know with regard to the loads experienced during the installation process where static or low-cycle fatigue failures are possible. The mechanics of the cable is of interest to reach the required performance at an acceptable weight [23].

The cable is supposed to withstand all mechanical stresses during manufacturing, transportation, installation and operation. Inappropriate mechanical design can cause less availability and high repair cost as it is left vulnerable to damage. The first challenge is to withstand tensional stresses when the cable is laid into the water. The armouring has to provide sufficient tensional strength. The cable weight, the residual bottom tension, and the dynamic forces on the cable when moving it up and down all contribute to the tensional forces on the cable when it is laid on the bottom.

There are other unexpected external forces that can raise the tensional stress on the cable. It is difficult to estimate those factors and there are no specific rules for the thickness and number of armouring wires. Most manufactures consider those factors design data not suitable for publishing. But there is a rule of thumb that more steel and harder wires provides better protection. Double wire armouring is also stronger than single wire armouring.

The thickness of the armouring wires influence the weight and diameter of the cable which influence the length in each shipload and laying schedule.

Bending stiffness is also of interest for subsea cable producers as it can change the bending radius at the touch down spot when the laying wheel moves down in heaving. The bending stiffness parameter is the friction between the cable layers and is dependent on temperature [21, 23, 24].

Dielectric strength

The dielectric strength is the maximum strength insulation can withstand without a failure or breakdown. The electrical strength is a material property and is expressed in kV/mm and is lower for thicker insulation layers as there are increased numbers of impurities which can act as a starting point for a breakdown, even though the breakdown voltage is higher. The dielectric strength is dependant on e.g. temperature, voltage shape, and duration. DC cables are not subject to dielectric losses [21, 25]. It is important that the insulation is smooth and clean to avoid breakdown.

2.5 Summary

The most suitable technology for bulk electrical transportation through subsea power cable over long distances at high voltage rate is HVDC technology and extruded XLPE cables and mass-impregnated cables. The evaluation and development of this technology and operation experience will be described in the next chapter.

3 Development of the HVDC Cable System

Currently there are around one hundred and sixty HVDC systems that have been implemented or are under construction around the world according to the Institute of Electrical and Electronics Engineers (IEEE) [26], nine of them have been dismantled. Of those one hundred and sixty cables there are around sixty HVDC subsea cable systems and thereof approximately thirty five in Europe (excluding power transportation to offshore oil/gas or wind power platforms). The main reasons for those implementations are to increase energy security by interconnecting autonomous power grids or island to mainland, to increase the utility of renewable energy sources and to lower carbon dioxide emissions. All those cable projects contain major experience and technological development which is very important to study and take advantage of for the evaluation of other similar projects. That also helps further improvements and development of processes and technology in HVDC subsea cable systems. In this chapter the evaluation of European subsea power cables will be explored.

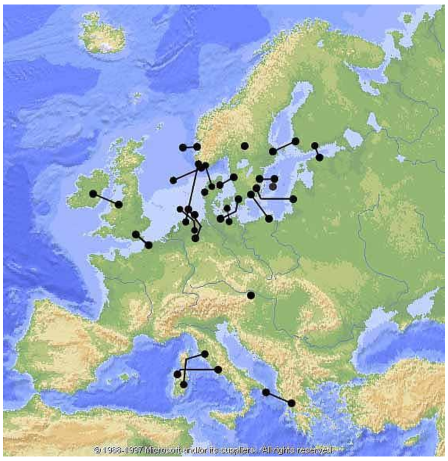

Figure 3.1 HVDC Subsea cable links in Europe [27]

In 1954 the first commercial HVDC subsea cable in the world was laid across the sea between Sweden (Västervik) and the island Gotland (Ygne) transmitting 20 MW at 100 kV. The Gotland link was implemented to supply the islands electricity demand and therefore lower the cost for industries and break the trend of unemployment and depopulation. With continuous increase in electricity demand there were two additional cables laid between mainland Sweden and Gotland, Gotland II (1983) and Gotland III (1987). It also meant that the oil-fired power station in Slite and the diesel stations in Visby could be decommissioned, and function as reserve sources of energy resulting in an enormous reduction of CO_2 emissions to the ambient.

Since the implementation of the Gotland link there has been a great increase in power capacity and voltage rating through HVDC subsea power cables, as seen in Figure 3.2.

Those figures show the performance evolution for HVDC subsea cables and are listed in Table 3.1.

Table 3.1 Evolution in power and voltage in implemented cable links

Cable link	Commissioning year	Power (MW)	Voltage (kV)	Location
Gotland I	1954	20	100	Sweden
Konti-Skan 1	1965	250	250	Sweden – Denmark
Skagerrak I	1976	275	250	Denmark - Norway
Cross channel	1985	500	270	France – UK
Konti-Skan 2	1988	300	285	Sweden - Denmark
Fenno-Skan	1989	500	400	Finland – Sweden
Baltic Cable	1994	600	450	Germany - Sweden
NorNed	2008	700	450	Norway - Netherland
Sapei	2010	500	500	Italy
Fenno-Skan II	2011	800	500	Finland - Sweden

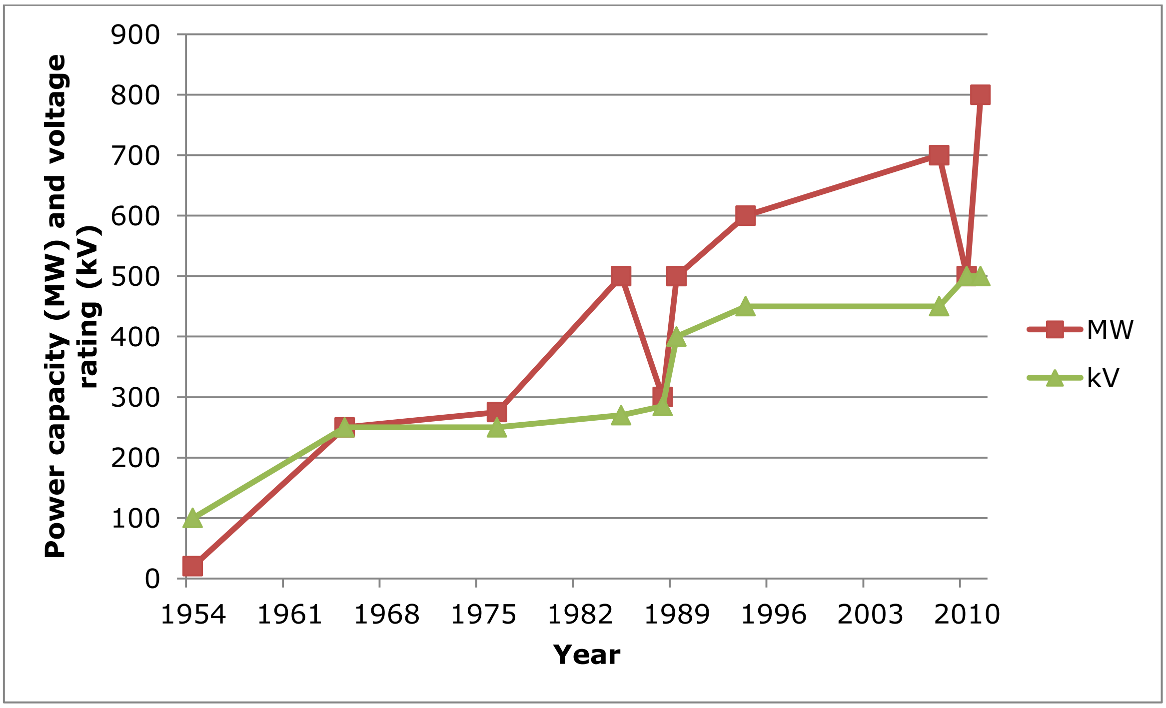

Figure 3.2 Evolution in power and voltage in implemented cable links

The data used in Figure 3.2 is according to an IEEE list of HVDC projects in operation. Every milestone on the graph shows the first implementation of a HVDC subsea power cable system at higher power capacity (MW) and/or higher voltage rating (kV) than prior cable systems. Power capacity and voltage rating for each milestone for a specific year belong to the same HVDC cable link implemented at that time. The power capacity is for one pole. Some cables are bipolar and therefore transfer two times the given capacity in Table 3.1. For example the Sapei link transmits 1000 MW through bi-pole system with each transmitting 500 MW. The Cross Channel cables transmit a total of 2000 MW through two bipolar links where each bi-pole is transmitting 1000 MW.

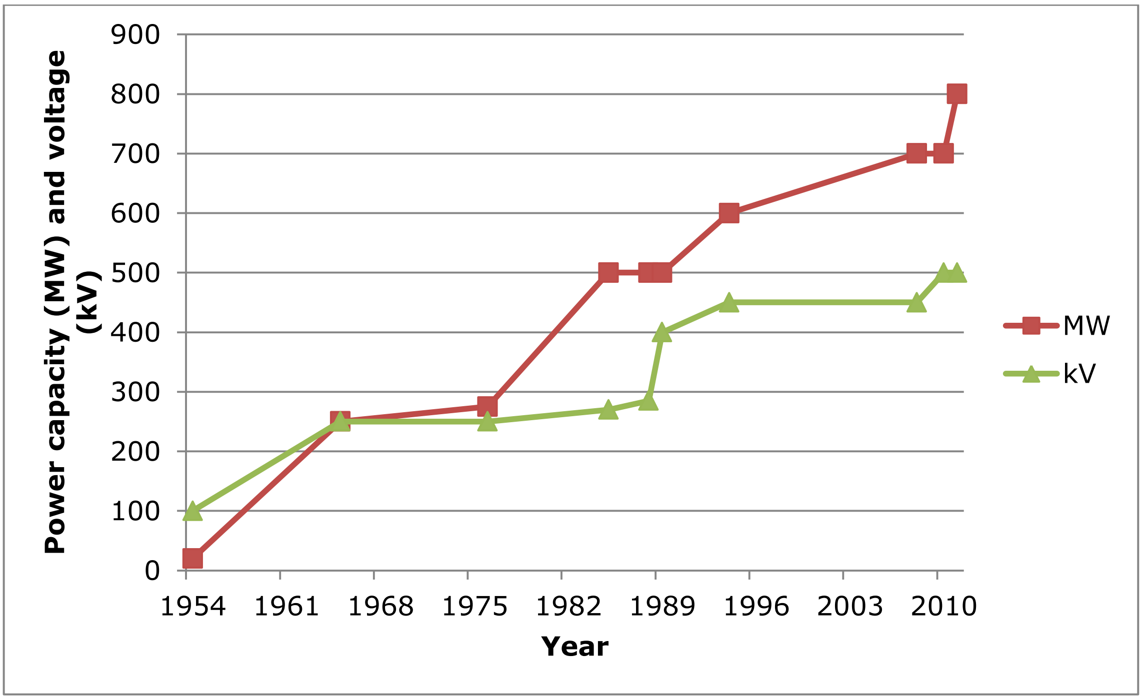

Figure 3.3 Evolution in power capacity (MW) and voltage rating (kV)

The highest implemented value in each year for power capacity and voltage is shown in Figure 3.3 to give a clearer picture of the cable performance evolution. The technology develops to transmit electricity at higher voltage to reduce the ohmic losses as Equation 2-3 states.

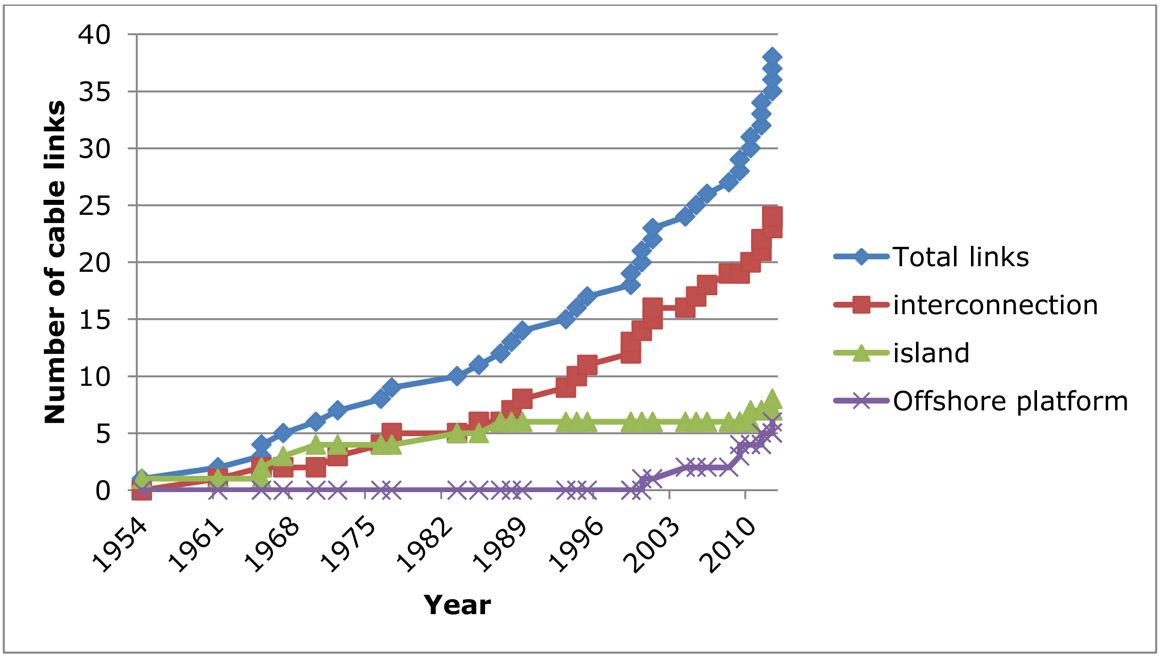

Figure 3.4 Cumulative HVDC subsea power cable links implemented each year

Total HVDC subsea power cable links in Europe is approaching forty and the majority, or 59%, are interconnection of power grids. During the last sixty years of development more than 50% of all links have been implemented over the last 10 years. At the end of the twentieth century there were rapid implementations of HVDC cable links. Prior to the Skagerrak 1 cable link implementation a feasibility study was done showing the great advantages obtained by connecting those two energy systems [28]. Danish power plants can supply Norwegian demand on off peak hours, when Norwegian power plants are short of water due to lack of rainfall. And conversely Norwegian excess power can save oil/coal in Danish power plants. Further building of power plants in Denmark could be postponed. There are also mutual stand by if there is a breakdown in power plants in Denmark or Norway. That increases energy source mix and security.

This is at a time when industrialised societies are interested in the gaseous waist flow of fossil fuel combustion, first because of acid rain and health impacts and now mainly because of massive emissions of CO_2 [29].

Europe, and specially the Nordic countries, is facing increasingly challenging goals in lowering CO_2 emissions and turning to renewable energy utilization for electricity generation [5, 30]. A high-voltage DC power highway has been developing between countries in Europe, resulting in greater energy source flexibility and better utilization of renewables. That lowers the CO_2 emission and increases energy security [1, 2]. Looking outside Europe the same trend has occurred all over the world. In Africa and Asia there has been laid extremely large HVDC underground cable links to interconnect sections of the continents to lower CO_2 emissions and increase energy security.

The environmental concerns are a strong driving force for technological development to be able to overcome the above mentioned challenges countries and continents are facing. In the next chapter the technological experience of HVDC subsea power cables is summarised to be able to analyse state of the art and the latest trends.

3.1 Cable design

This chapter will summarize the experience from HVDC subsea cable systems.

The design of the conductor size and insulation thickness of a subsea power cable is dependent on thermal, mechanical and dielectric stresses applied to the cable system. A cable design depends therefore on marine environment, protection needs, permission requirements, installation method and operational requirements. These conditions vary along the cable route, hence calling for an adapted design for different sections. Only full consideration of all aspects can result in a successful project [21, 31, 32].

After a thorough marine survey with regard to, requirements, permissions, installation and operation the thermal conditions along the route can be determined together with the protection needed so the design of the cable can begin. The experience can help evaluate what technology is appropriate for different conditions in different projects. The design of the cable is highly dependent on the material properties and the experience demonstrates few available material types that are suitable for high-voltage DC power transmission.

The main subsea power cables are XLPE cables, extruded XLPE cables, oil-filled cables and mass-impregnated (MI) cables. Their name is usually based on their insulation material. Different cables are used for different applications as shown in Table 3.2. The main subsea power cables for bulk DC transmission over long distances are extruded XLPE cables and MI cables.

Table 3.2 Main subsea cable insulation and their applications

	XLPE	XLPE	XLPE or oil/paper	Extruded	Mass-impregnated
Voltage rate	33 kV AC	150 kV AC	420 kV AC	320 kV DC	500 kV DC
Power rating	30 MW	180 MW	700 MW / three cables	1000 MW / two cables	800 MW / cable
Length	20-30 km	70-150 km	< 50 km	> 500 km	>500 km
Usual application	Supply of small islands, connection of offshore wind platform	Connection of islands with large population, offshore wind platform	Crossing of rivers with large transmission capacity	Long distance connections of offshore oil and wind platforms	Long distance connections of autonomous power grids

3.1.1 Extruded XLPE cable

Extruded XLPE cable development has overcome the problems with the XLPE cables, as described in Chapter 2.4.1. Extrusion makes the surface smooth which reduces the stresses and the cables are installed close together in bipolar pairs with anti-parallel currents, thus eliminating the magnetic fields [19, 32, 34].

Extruded cables use cross-linked polyethylene (XLPE) as insulation. The insulation is most often extruded over a copper conductor (not aluminium) and covered by a water tight sheath, usually of extruded seamless lead for subsea cables, and a further protective polyethylene plastic coating. The armouring is made of galvanized steel wire to increase the cable´s tensile strength to tolerate installation stresses. The armour is usually a single layer of wires helically wound around the cable but for deep ends or rocky seabed often double layers are used. To inhibit corrosion the armouring is soaked in bitumen impregnated polypropylene yarn [23, 24]. By applying the steel wires in opposite direction to form a counter helix the torsional stress is eliminated [28, 32, 35].

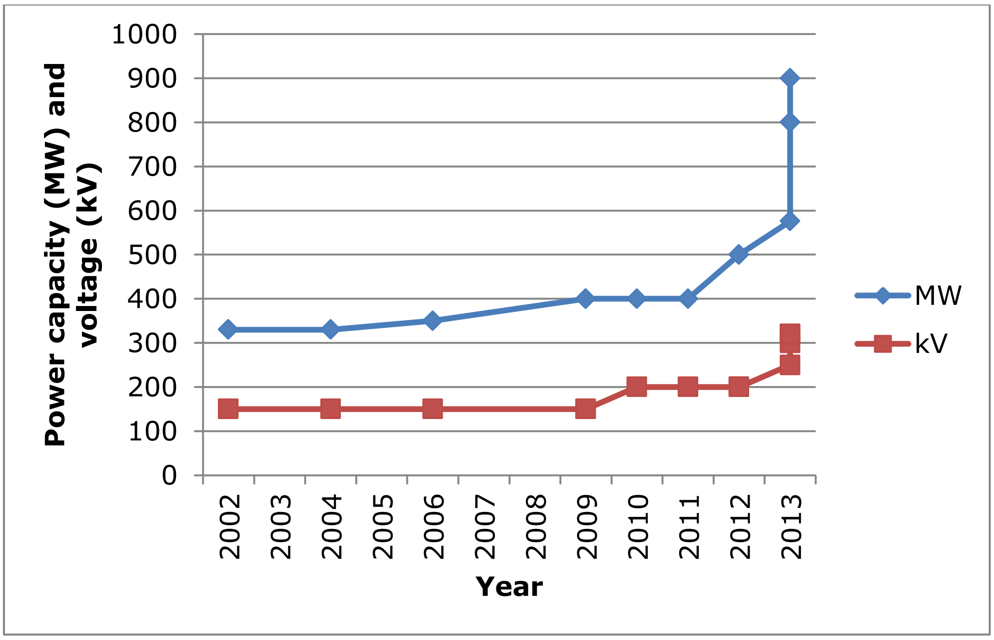

Figure 3.5 Evolution in capacity load, power and voltage, for extruded XLPE HVDC subsea power cables

Extruded XLPE cables are a relatively new entry to the HVDC subsea cable market with the first installation of the Cross Sound cable in 2002, transporting 330 MW at 150 kV. XLPE insulation is mechanically robust and they withstand higher temperature (90ºC) than the mass-impregnated cables. That allows them to carry more current for a given conductor cross section [17, 18, 25].

A major application of this type of cable are offshore wind and oil platforms but it has been used for interconnection of power grids. The Extruded XLPE cables transmission capacity can reach up to 1000 MW and voltages are available up to 320 kV. The extruded XLPE cable is not limited by the route length or power capacity, it is limited by the voltage rating of 320 kV [36]. With the latest technology HVDC extruded XLPE cables can be laid in deep waters and on rough bottoms over a long distance and they are environmentally friendly as the magnetic fields and risk of oil spill are eliminated. They continue to further develop with thinner insulation resulting in high-stress dielectrics [18, 25].

3.1.2 Mass-impregnated cable

Mass-impregnated cables are a mature technology and have been in operation since 1954 with the implementation of the Gotland I link. The mass-impregnated cable is the only alternative for a 500 kV voltage. There is no limit to length of the mass-impregnated cable because of the high viscosity compound used. They will also not leak due to damage because they contain fluid with a very high viscosity and are therefore environmentally friendly. Mass-impregnated cables weigh more than extruded XLPE cables and their cross section tends to be larger for an equivalent rating. The paper insulation used is similar to the extruded insulation, smooth and clean [19].

The conductor is usually copper due to the operation temperature (55ºC) for this type of cable but aluminium has been used in deep cold water parts [19] [18] . At greater depth the internal pressure of the cable increases and the laying tension also. That might limit the cable size and the power capacity of the cable. The laying tension may be lowered by reducing the cable weight. Aluminium is lighter than copper and is therefore more suitable for these conditions. Table 3.3 shows the mass and cross section of copper and aluminium conductor with the same resistance. For the deep part in the Sapei link (1620 m depth) this concept was utilized [37].

Table 3.3 Cross section and mass of copper and aluminium conductors at same resistance

	Cu-conductor	**Al-conductor**
Conductor resistance at 20C (mΩ/m)	0.015	0.015
Cross section (mm^2)	1200	2000
Mass of conductor (kg/m)	10.7	5.4

The insulation is made from layers of high density oil impregnated papers. The insulation is infolded with lead sheath covered with a plastic corrosion preventing coating. The armouring is helically wound around the cable of galvanized steel wire covered in bitumen impregnated polypropylene yarn to prevent corrosion [19]. For deep waters or rocky sea bed double layer armouring is used for protection. Double layer is e.g. used in the NorNed link and the Sapei link.

It was already known in 1988 that the cable system could transmit higher voltage than 250 kV and be laid at deeper sea level than 530 m. Mechanical and electrical tests were done according to CIGRÉ (International Council on Large Electric Systems) Study Committee No. 21 on mechanical test requirements depending on the sea depth and the weight of the cable in water, followed by electrical tests, which all cable system must undergo prior commissioning. The tests were done for cables that should withstand Skagerrak requirements, 275 MW, 250 kV, at 530 m depth, and it did no harm whatsoever to the cable insulation or other components of the cable, indicating that the present forces did not represent the limit. Tension tests were done with tensions up to 72 metric tons, which corresponds to the test required for a cable laid at 1620 m depth. According to the results a rated voltage level of up to 500-600 kV was seen to be within reach and it was estimated that the cable could be laid down to 2000 m, using copper ends and aluminium conductor for the deepest part [28]. Further research and development needs to be done.

Mass-impregnated power cables are available for single cable up to 800 MW and 500 kV. The longest cable route is 580 km long, the NorNed cable, and the deepest is 1620 km deep, the Sapei link.

For underground and subsea DC cables, extruded and mass-impregnated cables are competing at higher and higher voltages. There is on-going research and testing for a voltage rate of 500 kV for extruded DC power cables and it is expected to be announced in operation in only a few years [18, 38]. It is argued that the extruded XLPE cable is better than mass-impregnated cable due to its combination of low material, processing cost, reliability, and appropriate electrical and mechanical properties [17, 25].

The development of cable technology is incremental and a big part of it is related to materials and manufacturing processes. The insulation material development focuses on even better cleanliness, and better process ability for manufacturing. The performance of the cable is very dependent on the contaminants in the insulation (or insulation interface) which requires minimum impurities. Some of the material development is targeted at allowing longer extrusion lengths as they decrease the number of joints and the resulting simpler cable installation. Cleaner materials provide higher reliability and higher stresses, which also provide thinner cables and fewer joints [39].

3.2 Joints

The making of a reliable joint is often the most difficult task during development. When they are laid at the maximum depth they need to withstand the same mechanical strains during laying as the cable itself [32, 40].

Fewer joints cause simpler cable installation. The numbers of joints are dependent on the cable type and the available extrusion length. For a long subsea cable connection the extrusion length is shorter for an XLPE cable than similar mass-impregnated cable which requires more joints. XLPE cable joints are on the other hand easier to install and require less time as they are pre-fabricated and therefore cost less.

The assembly of joints on an open sea is really challenging and requires extremely good planning, suitable equipment and highly specialised and well trained crew. With those factors and good weather the joints can be built safely. But inadequate planning or equipment can lead to water intrusion which could result in cutting away piece of the cable or even the need to use extra spare cable and extra joints.

3.3 Laying of the cable on the sea floor

When laying heavy subsea power cables for high voltage rate at great sea depths it is of the utmost importance to have a cable laying vessel with all necessary cable laying facilities and adequate knowledge and experience to handle the cable in a safe way. The installation process has developed substantially over the past 20 years [41]. The laying vessels are bigger with higher turntable, are more suitable for harsh weather conditions and are built with satellite-based navigation system. The cables are getting longer with developed manufacturing methods which make the installation easier and quicker as there are fewer joints. The oil and gas industry has gained a lot of experience which has been transported into subsea power cable installations along with all the experience from fibre cable installation. The marine survey can be done much more easily than before which allows a close up look at the sea bottom. And the development of remote operated vehicles has helped in a way no one could have imagined [41]. Remote operated vehicles (ROV) are e.g. used to monitor the best possible cable route between obstacles or pipe and cable crossings.

Still, the installation process is no easy game and needs to be done with excellent planning, significant knowledge and experience.

3.4 Cable protection

Subsea power cables undergo damages which result not only in outages and lost revenues for the asset owner but also high repair cost and maintenance. Cable protection has developed significant results in higher reliability of the cable system and greater utility of the asset.

Appropriate protection is essential and needs to be considered during the whole process of the subsea cable project, preparation, planning, installation and operation. The protection can be improved by proper cable routing, suitable armouring and when the cable is buried under the sea floor.

At planning and preparation stage the cable protection can be increased by proper cable routing. By use of a marine survey hazardous areas should be avoided such as where obstacles that could harm the cable are lying, hotspots or steep slopes. It could be more economical to bend the cable past those areas rather than spend money on a higher degree of other protection. The marine survey gives information about route conditions which gives necessary information when designing the armour of the cable.

The armouring of the cable is supposed to meet torsional forces during laying but are gradually strengthened to meet external violence and also possible forces over the cable route. As mentioned in Chapter 3.1 the armouring usually has more layers in greater depths to meet torsional forces during laying. The NorNed cable and the Sapei link have double layer armouring. The armouring should be designed with respect to each project as it influences the cable properties, such as bending stiffness and tensional stability. For harsh conditions in offshore wind and oil platform connections the armouring has been strengthened and made more dynamic to withstand the great forces of the sea and the moving dynamics of the platform.

The highest probability for external damage to the subsea power cable is in the shallower parts of the route. Therefore the cables have been protected with more massive steel wire armouring for the shallower parts and less protection for the deep parts, or below 500 m. However, more steel wire armouring gives better protection against fishing gear and anchor.

During the laying process of the subsea power cable, the cable is now more often protected against external violence in operation from e.g. fishing gear, anchors and stormy sea currents. Cables are more often being buried under the sea bottom or protection is being built around them. The main external protection methods are trenching and jetting. In both cases the cable is buried under the sea bottom but with different methods. Trenching is the most common method and is simply ploughing down the subsea cable. Jetting uses water nozzles to sink the cable down into the seabed.

For the NorNed link the whole cable was protected. Water jet trenching is the protection over almost 97% of the cable route and the rest has been given protection by rock dumping. External protection is the trend for the latest subsea cable projects but in the earliest projects they were just laid on the sea bottom and left there unprotected and vulnerable to damage.

The protection constitutes a considerable part of the investment in the subsea power cable project and should be considered very carefully. In Chapter 4.5 Causes of damage and the estimated burial depth is discussed.

3.5 Operation

When the cable has been installed it is supposed to operate trouble-free for decades. Proper operation tools and maintenance planning should contribute to a long and useful life of the cable asset with a high degree of reliability. In this chapter what an operator can do to improve availability is discussed.

In operation, the cable needs to be monitored to prevent undesirable conditions such as overvoltage, overheating, external violence, fatigue, etc. This requires a maintenance plan for the cable system. Real-time monitoring systems have become extremely important over the last decade as they provide early warnings for likely problems enabling reconfiguration of planned maintenance as necessary and maximizing of cable utility [18, 42].

Those monitoring instruments are:

- Cable temperature monitoring (distributed temperature sensing: DTS)
- Partial discharge detection (PD)
- Cable dependent voltage control (CDVC)

Cable temperature monitoring

DTS is an optical fibre-based temperature sensor joined into the power cable, or installed alongside the power cable, and is able to monitor the temperature along the cable. Most DTS have built-in capability to detect and localize fibre damage. Hot- and cold-spots and other irregularities can be detected by the DTS. By comparing data from the DTS over certain periods of time it is possible to detect if the cable has been washed away which makes it possible to send ROV to inspect the cable for damage or corrosion. Unburied power cables should be inspected regularly by divers or ROV to examine their status in their environment. DTS can also be used to calculate the ampacity of the link by also considering the ambient temperature. The temperature profiles from the system can be evaluated for dynamic power rating which can exploit thermal reserves in the cable system for temporary overloads.

Partial discharge detection (PD)

Partial discharge monitoring has reached sophisticated level for detection of defects, inhomogeneity and other flaws to evaluate future cable life. This data helps in update maintenance plan when needed.

Cable dependent voltage control (CDVC)

This control is designed for mass-impregnated DC cables and is in the HVDC converter station. The CDVC can temporarily lower the voltage rate, at reduction of power demand, without limiting the transmission capacity. That reduces the electric stress in the cable insulation and has the potential to increase the electric life of the cable. The voltage than returns to rated when demanded.

Mass-impregnated and XLPE cables and their joints are maintenance free because they have no oil volume that needs to be pressurized from the shore station. Fluid-filled cables do need, on the other hand, monitoring of the oil-pressure feeding system. A loss of oil indicated failure which calls for immediate procedure [18, 42].

The operation station are mostly remote and automatically controlled, there are few employees. The operation and control of the converter station and other components of the HVDC system are really similar to AC operation which is a known procedure.

3.6 Extension of cable life time

The key factors for a good operation, high reliability and extending the cable lifetime will be described in this chapter. The experience gained from the investigation of this paper and interviews with specialists in the field will be summarized to evaluate those factors.

The main factors to consider are:

- Thorough marine survey and weather analysis
- Choose well known technological solutions
- Protection of the subsea cable
- Monitor voltage rate and power capacity
- Assess conditions of components
- Maintenance schedule

For a successful subsea power cable project many factors needs to be considered and assessed thoroughly. On the planning and preparation stage, marine survey and weather analysis is essential for further stages of the program and will affect the reliability of the project. With a thorough marine survey obstacles, steep slopes and harsh environment can be avoided which could damage the cable during laying and operation. Lower starting cost can also result in lower reliability if it is done at the expense of important material measurements which might then result in many failures during operation, causing outages and highly cost consuming repair.

The major challenge for operator is to extend the life time of the system. The operator needs to optimize power capacity and assess condition of components. According to specialist [45], the crucial factors are to choose manufacturers that have experience in similar constructions, cable systems, installations, etc. and to choose well known technological solutions. New technology has less experience and are therefore often less reliable. It is also mentioned that protection of cables is very important. That is burial of the cable were possible or covering them. Especially in shallow water near the coast line, the cable should be protected against anchors and fishing equipment. At last it is mentioned that the operator needs to try not to overload the cables, which means that the conductor temperature does not become higher than its design values.

In addition, testing is also a crucial factor, both for installation and operation. That helps with guidance and improvements which increases reliability of the whole system. A good simulation and optimization of the whole process is also essential to evaluate and update maintenance schedule when necessary. It is therefore of the utmost importance to follow up on state-of-the-art and choose highly experienced knowledge for every factor. Cable lifetime is on average 30-40 years [19].

The most common reason for HVDC subsea power cable implementations are environmental reasons, as they lower the greenhouse gas emissions, therefore it is also important to assess the impact on the nature and living organisms in the cable surroundings, both during installation and operation. Those aspects will be discussed in the next chapter.

3.7 Summary

When looking over the development of the HVDC subsea power cable system, innovation is shown to be about component design, materials and their manufacturing, installation methods, logistic issues, testing, or a combination of these different aspects. In many cases the feasibility of subsea connections relies on the use of advanced technical solutions and specialised knowledge.

With the development of the extruded XLPE cables they have been competing at higher and higher voltage rate and reliability with the mass-impregnated cable, which is a mature and reliable technology.

As in most technological projects every factor is very important for a successful project. That is also the case for a subsea power cable project but preparation and installation play a big role in a reliable, long living cable system. According to a specialist in subsea cables working for Energinet.dk in Denmark the most changes have been in installation, testing and in the armouring material. The cables are therefore more reliable than they were a couple of decades ago. Subsea projects from the early days compared to today can be described as two different worlds of technology and methods. The cable properties are better with improved materials and manufacturing, the armouring is stronger and the technology and methods concerning installation are better. Today most cables are also protected against external violence by being buried. That conclusion is described in the contribution to this work in Chapter 1.1.

Future cable systems will transmit more power, will occupy less space, will involve less cost, will include monitoring systems, etc., and all these improvements are needed to be implemented in the near future. The need for interconnections between disconnected grids also gives new challenges for the subsea cable manufacturers. The subsea cable technology has to be further developed to meet depth and transmission capacity requirements. Installation of subsea cable systems at very deep water also give challenges for laying equipment and laying methods.

In the next chapter the development of cables reliability will be analysed and put in context with the technology development. It is interesting to see if the cables are more reliable than they were before.

4 Reliability

Industrialised countries depend on electrical reliability and are paralysed in cases of extensive power outage. The cable system is a very important part of the electrical power grid and therefore all phases need to be considered and evaluated in respect to reliability and failure statistics.

Subsea cables have taken damage since the early days, when a cable is laid down on the sea floor at great depth one might think that it is hardly accessible to human activity. The 150 years of experience of subsea cables has, on the other hand, shown that most cable breaks are caused by humans or external violence. Only a small fraction of subsea cable faults are caused by internal failure, which are imperfections in the insulation system of the high voltage cables, joints or sealing ends.

Subsea cables rarely have the redundant grid for back-up of most cables in the land transmission grid. A failure in the subsea cable could black-out an island or offshore oil/gas platform. It could also reduce revenues for offshore wind farms. Subsea cables interconnecting countries would not black-out a whole country but would lower the owner's revenues from power trading. For this reason the reliability of subsea power cables is an important aspect of each business model and has strong influence on the cable design.

The reliability assessment is most often used to determine the adequacy of generation and/or transmission to meet the load. The analysis also helps evaluate the level of investment needed in order to improve reliability. The reliability information can generally be used as the starting point for any availability assessment.

4.1 The data

The International Council on Large Electric Systems (CIGRÉ) is generally recognised as being the definitive source of information for transmission and distribution systems based on the access to large sample populations given that CIGRÉ is a global organisation.

A number of reliability surveys have been established by CIGRÉ for HVDC LCC converter stations. Due to limited experience and data concerning VSC converters, that configuration will not be considered. The data covers utilization and availability of many LCC HVDC systems around the world. The data also represents mean time before failure (MTBF) and mean time to repair (MTTR) for the overall system and the converter station [43].

There is clearly a need for HVDC subsea cable information. But with the great work by CIGRÉ the CIGRÈ brochure 379 [44] provides the most comprehensive source of service experience for both underground and subsea HVDC cable systems. The subsea cable data spans the period from 1990-2005. The data covers 7.000 km of subsea power cables both for HVDC and HVAC technologies. The failure rates are defined by insulation technology, operating voltage level (60-219 kV and 220-500 kV) and internal/external failures for both underground and subsea cables. Data from a similar CIGRÈ study on a HVDC subsea power cable system in 1986 will be used for comparison. Additional data was obtained from Svenska Kraftnät about failure statistics for HVDC subsea cables in Sweden [45]. The data covers five links for voltage rate > 150 kV. All cable types are mass-impregnated and the service period comprises 34 years in operation. Data about failure rates for several large HVDC cable systems was also analysed [42].

Data is collected for equipment populations over various lengths of time and does not take into account any consideration of the age of the asset. Further specific cautions about the data will be expressed in the chapters below where needed. Definitions of statistical terms will be described in the next chapter.

The availability data, MTBF information from CIGRÉ and other sources can then be applied with MTTR data together with maintenance assumptions to enable the future availability for an individual asset or system to be estimated.

4.2 Definition of statistical terms

Reliability can be expressed in many different ways which makes it critical to use well defined expressions [42, 46].

The utilization factor is the ratio of maximum demand of a system to the rated capacity of the system. Definition of power cable utilization is:

$$\frac{Total\ transm.\ energy\ during\ the\ year\ MWh}{System\ rating\ MW\ x\ 8760\ hours} \cdot 100 \qquad 4\text{-}1$$

Reliability is the probability that a cable is fulfilling its purpose adequately for the period of time intended. The reliability can be described as:

$$1 - (\lambda\ x\ r)/8760 \qquad 4\text{-}2$$

where λ is the number of failures per year and r is repair time after failure (hours). The number 8760 is the normal expected full hours of supply availability in one year.

Availability is a measure of a system´s performance in terms of its reliability and maintainability and is found by the formula:

$$1 - (\lambda\ x\ r + c)/8760 \qquad 4\text{-}3$$

where c is scheduled outage (e.g. maintenance) (hours/year).

Below are further definitions of more concepts used in statistical terms when analysing the electrical system:

- Outage is a period of non-functioning of the system, there is no power transported.
- Forced outage (forced energy unavailability, FEU) is involuntary outage as a result of a failure.

- Failure rate is the annual rate of forced outages associated with failures in the cable and is expressed in the terms of failures/year/100 cable kilometres.
- Scheduled maintenance is annual preventive maintenance as specified by supplier or according to operators own standards.
- Unscheduled maintenance is all maintenance required that cannot be termed annual preventive maintenance.

Mean time before failures (MTBF) is the predicted time (hours) between failures of a system during operation and is:

$$MTBF = 1/\lambda \cdot 8760 \qquad 4\text{-}4$$

How often outages occur, or the frequency (failures/hour) is:

$$f = 1/MTBF \qquad 4\text{-}5$$

Mean time to repair (MTTR) estimates the time it takes to restore the system after failure. Mean time to failure (MTTF) is then:

$$MTTF = MTBF - MTTR \qquad 4\text{-}6$$

If MTTF >> MTTR then $\lambda \approx f$.

4.3 Utilization

Energy utilization is the actual amount of energy transmitted through a HVDC system. The utility is expressed as a percentage based on the maximum continuous capacity of the HVDC system. It differs between systems how much is transmitted as Figure 4.1shows. Those links who operate at very low energy utilization are used for peak load and excess capacity, or for standby capacity, while other systems are used more when closely approaching maximum rated capacity.

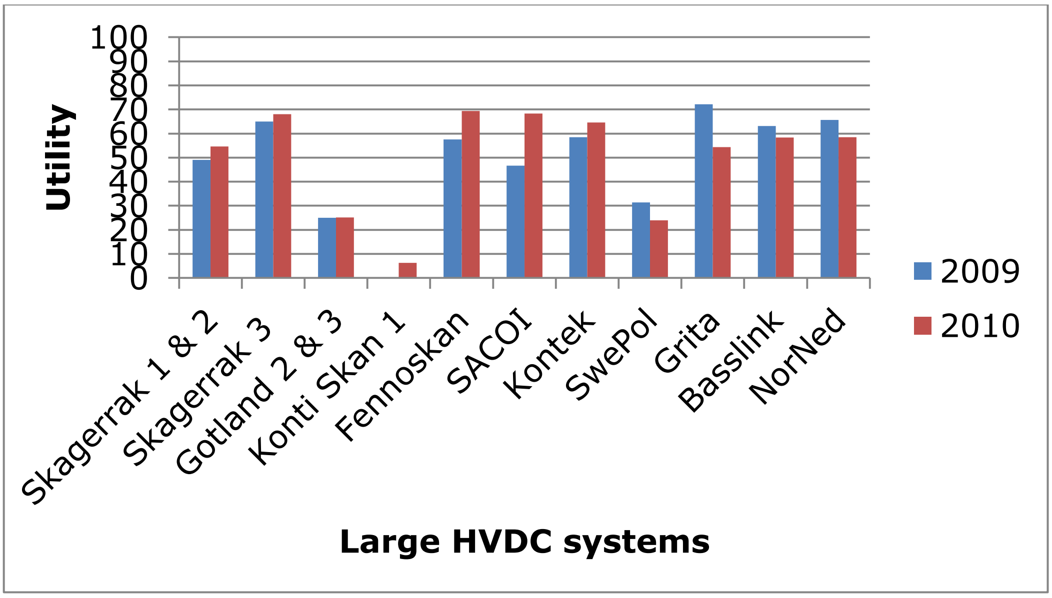

Figure 4.1 Utilisation for several large HVDC systems 2009 and 2010 [43]

The data in Figure 4.1 shows several HVDC links described in the CIGRÉ reliability survey in 2009 and 2010. The average energy utilization of the HVDC systems was 53,4% and 53,3% in 2009 and 2010, respectively [43]. The Konti Skan 1 cable system had a failure in the converter station resulting in almost total outage both in 2009 and 2010. If the Konti Skan link is ignored the average utilization reaches 57,5% in 2010. There was no data for Konti Skan during the year 2009 so the average utilization is unchanged.

4.4 Energy availability

Energy availability is the measure of total energy that can be transmitted except what is limited by forced and scheduled outages of converter station equipment and transmission lines and cables. The availability is expressed as a percentage based on the maximum continuous capacity of the HVDC system. A subsea cable link with high availability increases energy security by satisfying practically all requested demand for energy.

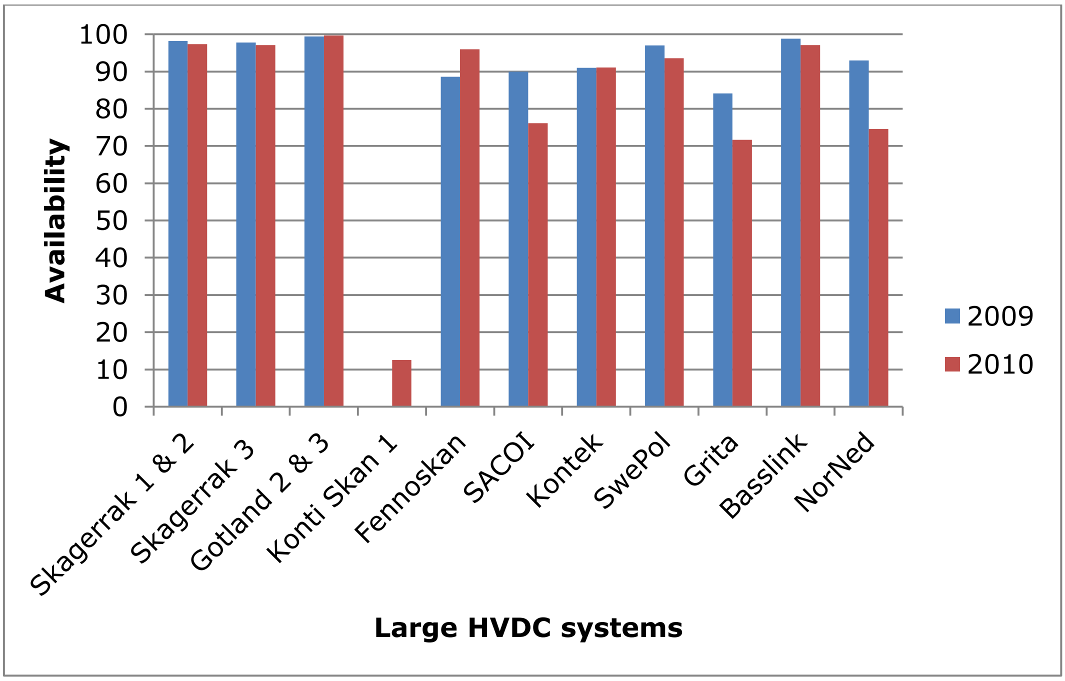

Figure 4.2 Availability in several large HVDC cable systems 2009 and 2010 [43]

The average availability from the CIGRÉ study was 95,2% and 91,9% in 2009 and 2010, respectively. Figure 4.2 represents the outcome of a CIGRÉ study concerning the availability for several large HVDC cable systems in 2009 and 2010. Ignoring the Konti Skan 1 cable the average availability in 2010 would be 94,2% and unchanged for 2009 because there was no data for Konti Skan 1 for that year [43]. In 2010 the availability is not showing good results due to the fact that Konti Skan 1 is facing continuous outage from 2009 and both the SACOI cable link and NorNed cable encounter long durations of forced outage due to cable failures. The outages will be further discussed in following chapter.

Table 4.1 Average availability for HVDC cable systems

Year	2006	2005	2004	2003
Average availability (%)	93,4	94,0	95,2	92,6

Table 4.1 is according to CIGRÉ surveys in 2003-2004 and 2005-2006 showing the average availability for HVDC cable systems. The table demonstrates that the availability is similar between the years.

The average figures will only be realised in practice because one or two projects will suffer from major events, thus having very poor availability, whilst most projects will actually achieve better than average availability. Total unavailability for a HVDC system is categorised into forced outages and scheduled outages. Forced outages are when there is unforeseen damage to the cable leading to no power transmission. Scheduled outages are due to scheduled maintenance which is done in accordance to an operation maintenance plan. The maintenance schedule differs between projects. The main cause of forced outages and how to lower the risk of failure is discussed in the next chapter.

4.5 Cause of damages

Forced outages are unforeseen damage to the system causing no transmission of electricity. Failures to subsea power cables are grouped in two categories: external failures and internal failures. Most damage is caused by external violence which can be classified by failures caused by natural causes and human activities [47, 48]. Internal failures are due to joint failures or electrical damage. Failure rates for external and internal damage are described in the next chapter.

Natural causes of damage are mainly due to tides and waves and moving materials on the seabed. That causes corrosion and abrasion, respectively. Other natural causes are movement of the sea bottom, tsunami and shark bites. The external violence to subsea power cables is mainly caused by anchors and fishing equipment. Ocean dumping of material and other cables can also be harmful to subsea cables.

The reliability of the subsea power cable is to a large degree dependent on avoiding ship anchors and fishing trawlers [48, 49]. Ship anchors and fishing activity is causing most subsea cable failures, both for telecom cables and power cables [47]. Figure 4.3 shows the cause of damage to telecom cables in the Atlantic Ocean which can be used to evaluate cable route and protection for the cable and therefore lower the risk of forced outages in the HVDC system.

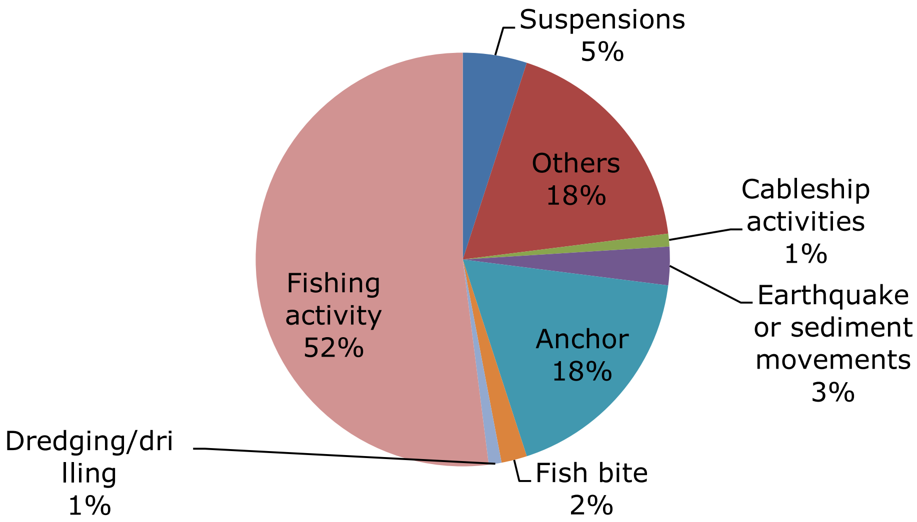

Figure 4.3 Cause of damage to telecom cables in the Atlantic [48]

Fishing activity includes for example trawling and dredging. Trawling equipment cuts, in soft grounds up to 30-40 cm deep into the seabed. Under unusual conditions the trawl net can go much deeper into the seabed. The force impact from a trawl net is estimated at 11 tons and the pulling forces can destroy almost every subsea cable laying on the sea floor. Dredging activity is designed to stir up the sediment and harvest shellfish and they dig approximately 450 mm deep into the seabed.

Neither trawling nor dredge fishing is expected to disturb the seabed to more than 0,5 m in depth [48]. For a burial depth deeper than 1m into seabed the risk of interference is therefore low. However the bathymetry is not always stable and can move with time and expose the cable to external threats.

Anchor damage is the second biggest single threat to subsea cables. For subsea power cables, due to their larger diameter and strength, anchor damage is probably at the same level as fishing gear damage or even exceeds it. Anchor damage mostly occurs due to involuntarily anchor drops for emergency. Anchor damage happens in harbour, ship lanes and in open sea. The most common depth for anchor damage is however at less than 100 m depth. About 98% of anchors are at 8000 kg or below, and more than 60% are below 4000 kg [48]. With more weight of anchor the ability to damage buried cable increases. Heavier anchors can penetrate deeper into the seabed and cause greater damage with a hit than lighter anchors. Heavier anchors belong to heavier vessels which can drag and damage with greater force than a smaller vessel with a smaller anchor.

Table 4.2 Relationship between ship size, anchor weight and penetration depth in mud and sand [24]

Ship weight (tons)	Anchor weight (tons)	Penetration depth in mud	Penetration depth in sand
1.000	1,0	~ 1,0 m	~ 0,5 m
5.000	2,8	~ 2,0 m	~ 1,0 m
15.000	4,6	~ 3,0 m	~ 1,5 m
50.000	8,2	~ 4,0 m	~ 2,0 m
100.000	12,4	~ 5,0 m	~ 2,5 m

The relationship between ship size, anchor weight and penetration depth is show in Table 4.2. This is a study for Japanese waters but does not specified what ship tonnage unit is used. Another reference about the relationship between ship size, anchor weight and penetration depth is show in Table 4.3 [48].

Table 4.3 Relationship between ship weight and anchor type and penetration depth in firm ground (sand/clay) [48]

Ship weight (Gross tons)	Danforht/Moorfast penetration depth	Stockless / AC14 penetration depth
2.000	~ 1,5 m	~ 1,2 m
4.000	~ 1,7 m	~ 1,35 m
70.000	~ 1,9 m	~ 1,45 m
100.000	~ 2,1 m	~ 1,5 m
130.000	~ 2,2 m	~ 1,5 m

A burial depth of 1,5 – 2 m is a good measure to avoid anchor damage in these particular waters. A similar conclusion can be expected for most shipping areas but a similar risk assessment for other cable routes should be performed, based on local shipping traffic.

4.6 Repair cost

According to Svenska Kraftnät [45] the operation and maintenance costs for subsea cables (not including the converter stations) is generally quite low. Maintenance costs for subsea cables are mostly related to costs for storage of spare cables or spare parts. Also some lower costs for inspections of equipment placed on shore and some sea bottom inspections made by divers. The total cost for maintenance is estimated at less than 100.000 SEK (or less than 12.000 EUR) per year for each HVDC link.

Table 4.4 Total investment cost for several large HVDC cable systems

	NorNed	Sapei	BritNed
Investment cost (million EUR)	600	750	600

However, subsea cable repair is very expensive. The experience from Svenska Kraftnät shows that a subsea cable repair will cost something between 65-85 MSEK (or 7,5-10 million EUR). Investment cost for HVDC systems is estimated at 1,0 million EUR per km, according to Table 4.4. Repair cost for one failure of a 500 km long cable is then almost 20% of the total investment cost [45]. The repair cost is dependent on the vessel needed, removal of mechanical protection needed, repair of the cable, availability of resources needed and damage to the environment [47].

4.7 Repair time for subsea power cable

The repair of damaged subsea power cables is a demanding task. The main activities for the repair of subsea power cable damage include [44, 48]:

- Fault location
- Mobilisation of vessel, equipment and crew to uncover the cable
- Uncover the cable
- Mobilisation of vessel, equipment and crew to perform repair
- Wait for weather window
- Time for the repair itself
- Protect cable

The repair time in the case of a cable failure is different depending on the fault location, mobilisation time of the vessel and weather conditions.

The waiting on weather window (WOW) is a really costly way of doing nothing. That is the time when the repair vessel with its specialised crew and equipment is waiting for acceptable weather to work. The sea state limit is different for various operation criteria. Remotely operated vehicle (ROV) cannot operate in as harsh weather as divers. The North Sea experience with regards to typical intervals for maximum operating sea state for different types of operation is listed in Table 4.5.

Table 4.5 Typical maximum sea state for different types of operation (expressed in wave height $H_s(m)$)[50]

	ROV	Diving	Lift operations
Max wave height	3-5	4 – 6	2,5 - 3,5

To perform a repair operation on the subsea cable a minimum weather window is assumed to be seven days. It is also assumed that the operation can be fairly easily stopped at certain steps and continued in the next weather window. Wave height is evaluated from the typical maximum sea state in Table 4.5 and is not assumed to exceed 3,5 m.

According to a study of the North Sea the waiting on weather time is shown in Table 4.6 [51].

Table 4.6 Waiting on weather time in the North Sea

Period	Days
Oct – Jan	40 - 45
Feb – Mar	25
Apr – May	5
Aug – Sep	5
Jun – Jul	2

That gives an average of 17 days on WOW and the total average repair time is shown in Table 4.7 [44, 52].

Table 4.7 Assumed subsea power cable repair time

Activity	Duration time (days)
Fault location	5
Mobilisation to uncover cable	10
Uncover the cable	3
Mobilisation to perform repair	12
Wait for weather window	17
Time for repair itself	10
Total	57

In Table 4.7 it is assumed that operation of the cable can start before the cable is fully protected again. Some activities can start before other activities have been completed. That assumption could lower the assumed repair time to 40 days. The average repair time for Swedish cable links is 65 days [45].

The weather contingency in the above table is based on typical weather delays in waters around the North-Sea. During extreme weather conditions such as storms and sea-ice, the overall repair time could increase significantly. Small cables in calm weather can be repaired within two weeks. For larger cables more specialised vessel, equipment and crew is required, but if spare cable and parts are available the downtime of the system can be between a few weeks and four months [48]. In the 2009 CIGRÉ study on subsea cable experience [44], 14 out of 49 faults were repaired within a month.

To assess the reliability of a subsea power cable link it is essential to know the cable availability and failure rate. That will be discussed in the next chapter.

4.8 High-voltage subsea cable failure statistics

Forced outages are the main source of HVDC subsea cable unavailability. Maintenance is mostly limited to mechanical protection work and can usually be performed with the cable energised. Failures are grouped into two categories: internal failures and external failures. Several studies and data will be analysed in this chapter and will be used to evaluate the cable base case for Icelandic conditions.

4.8.1 CIGRÉ study

The study from 1986 showed a failure rate of 0,32 failures/year/100km [42]. At this time only a small fraction of the cable kilometres were protected. According to the study 82% of the failures occurred in the cables and 18% in the joints. A majority of the cable failures were caused by external violence and the joint failures were caused by poor engineering, installation or maintenance. Many of the cables were oil filled cables and their joints were more complicated than for XLPE and mass-impregnated cables. With better understanding of cable properties the joints are more reliable today.

In the 2009 CIGRÉ study [44] about subsea cable experience, there were 49 failures reported for approximately 7000 km of subsea power cables, only 4 of them where internal. Three of the internal failures belong to the same cable installation.

Table 4.8 Failure rates 2009 for subsea power cables > 60 kV expressed in (failures / (year x 100 circuit kilometres))

Cable types	Internal origin failures	External origin failure	All failures
AC HPOF	0	0.7954	0.7954
AC LPOF	0	0.1189	0.1189
AC XLPE	0	0.0706	0.0706
DC MI	0	0.1114	0.1114
DC LPOF	0.0346	0	0.0346

Table 4.8 represents the results in the study from 2009. All cables, except the HPOF (which is not used very often today), have better failure rates than in 1986. The measurement is for each circuit kilometres but some cable links do have more than one cable. Taking that into account the failure rate would be lower. The ratio of joint failures changed from 0,22 to 0,095, from 1986 to 2009, respectively [42]. This demonstrates that the cable joints are safer today and the cables are more reliable than in 1986. Those results confirm that the development in HVDC cable systems described in Chapter 3 have increased the cable reliability. The results also show that the majority of subsea cable failures are due to external violence.

4.8.2 Large HVDC cable failure rate

Additional data illustrating failure rate for large HVDC cable systems in 1998 [42]. Show results of 0,264 failures/year/100 cable kilometres for mechanical faults and 0,0143 failures/year/100 cable kilometres for internal faults. Included in this data is the 1964-1988 Konti Skan 1 link which suffered many mechanical failures, when excluding that link the failure rate drops to 0,1 failures/year/100 cable kilometres, as seen in Table 4.9.

Table 4.9 Failure rates and repair time of large HVDC subsea power cables in 1998

	Internal failure	External failure	Total failures
λ_{km} (failure/year/100 km)	0,0044	0,1010	0,1054

Those results further verify that a few cable systems contribute largely to failure statistics and the majority of subsea cable failures are caused by external violence. The mean time before external failures is approximately 6 years but 139 years for internal failures. The unavailability due to subsea cable failure is 2,55% which gives a cable reliability of 97,45%.

4.8.3 Swedish subsea power cable failure statistics

In Sweden there are five HVDC subsea cable systems. The data from Svenska Kraftnät are for approximately 1400 km of subsea power cables and during their operation there have been 28 failures reported, of these 5 are internal failures. Two of those internal failures belong to the same cable and were insulation failure, the other three belong to another cable and were because of a high voltage fault.

Table 4.10 shows the failure rates causing forced outages for the Swedish HVDC subsea power cables of mass-impregnated cable type during 34 years of operation. The calculated mean times are also listed in Table 4.10 for the Swedish cable links.

Table 4.10 Cable failure rates and repair time of Swedish HVDC links

	Internal failure	**External failure**	**Total failures**
λ_{km} (failure/year/100 km)	0,0186	0,0855	0,1004
MTTR (years)	0,1780	0,1780	0,1780
MTBF (years)	44,0000	9,5652	
MTTF (years)	43,8219	9,3871	

The average time before external failure within the Swedish subsea cable links is nearly 10 years and 44 years for internal failure. The unavailability due to subsea cable failure is 2,65% which gives cable reliability of 97,35%.

4.9 Summary

The average utilization for large HVDC subsea cable links has been around 53% over the last years with energy availability around 93%. Decrease in energy availability is because of scheduled maintenance causing outage of the system, or no electric transmission through the cable, or due to unforeseeable damage to the system, mostly the cable system. The main causes of damage are due to fishing activities and anchors and the main issue to increase reliability of the subsea cable is to avoid those activities. The reliability is dependent on how often damages occurs over a year and how long it takes to repair the damage and restore the system again. The damage statistics is 0,1 outage/year/100 km. For subsea cable the repair time can be quite long, depending on location and weather. The waiting on weather window is different between seasons and locations and differs quite a lot. The average time to repair damage is approximately 60 days.

5 Environment

Environmental assessment is necessary for all industrial projects and is crucial for licensing and permits. Environmental impact assessment is a tool to evaluate and identify the probable environmental consequences of certain proposed development actions. All those who intend to enhance a subsea power system project must perform environmental impact assessment according to EU directives 97/11/EG and 85/337/EEG. They regulate the legal background for the assessment. Laws, rules and requirements regarding environmental impact can differ greatly between countries, and even projects. When evaluating the environmental impact from a subsea power cable system it is important to do a "null" analysis. Null analysis evaluates environmental impact if the project is not implemented. For subsea power cables that is often an increased use of coal fired power plants.

This chapter will discuss the major environmental impacts from subsea power cables and the findings as discussed in the contribution in Chapter 1.1.

5.1 Environmental impacts

5.1.1 Installation

The laying process is a slow activity. There is no gas or oil leakage from the vessel, except the normal exhaust from the engine. The waste is stored and processed according to vessel standards. The noise is similar to other vessels. When the vessel is near beaches there might be low-frequency noise and an exhaust smell. The vessel can disturb marine wildlife especially during reproduction periods. Legislative authorities usually restrict cable laying time to avoid periods of wildlife mating and breeding.

Most cables today are buried and that might impact the sea floor. A burial depth of 1,5 – 2 m is common to avoid anchor damage as described in Chapter 4.5. The trenching gear required usually stirs up a lot of sediment but this settles down after a short period of time, depending on the soil sediment and trenching method. In many cases the route is invisible within a year after burial. That was the case with the SwePol HVDC cable in the Baltic Sea [53, 54]. The installation is a one-time operation and then the cable lays there undisturbed, except in the case of repair the seafloor is not disrupted again. In comparison to fishing activities, trawling and dredging do dig down into the seafloor and drag equipment along the seafloor with great force, under normal operation not deeper than 0,5 m. Such activities are continuous.

5.1.2 Operation

Thermal impact

Electrical transmission cables do dissipate losses in the form of heat. Cables installed on the seafloor do not heat up their surroundings as the water washes almost all heat away. Buried cables can heat up their surroundings in the long run and the cable surface can reach 40-50ºC. This is however an extremely rare condition because most subsea cables do not operate at full load. The temperature decreases with distance from the cable and a few meters from the cable there is little warm up of the sediment [54]. Authorities have recommended a limitation to temperature rise based on burial depth of the cable, especially in sea in national parks or very sensitive areas.

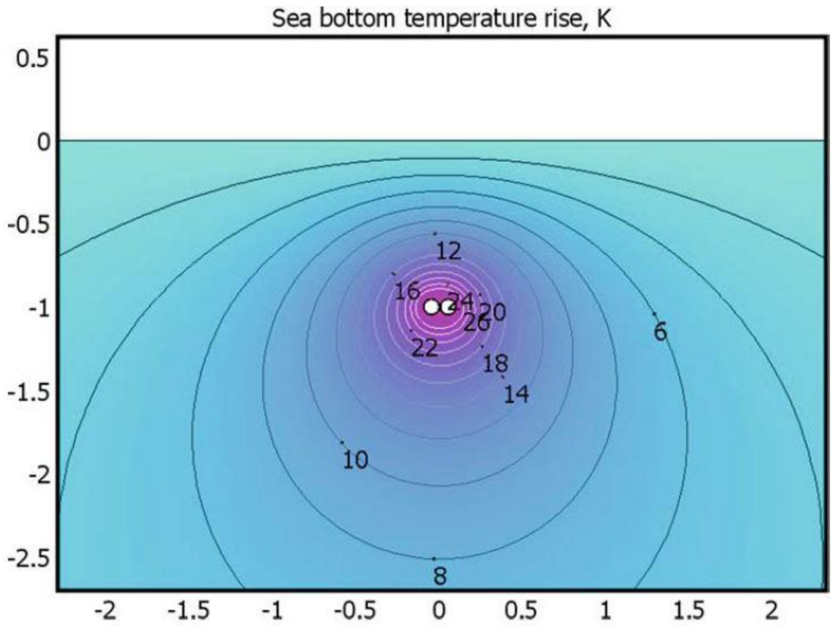

Figure 5.1 Isothermal lines around two HVDC cables. The x- and y-axis represent horizontal and vertical position, respectively, expressed in m. [54]

The isothermal lines of temperature rise in sediment around subsea power cable that has been buried 1m under the seafloor are shown in Figure 5.1 It is a pair of 100 mm^2 HVDC cables each with heat loss of 30 W/m. The temperature does decrease with distance from the cables.

Electromagnetic fields

Electromagnetic fields are electric fields and magnetic fields. There is no electric fields outside HVDC subsea power cables as the armouring efficiently confines the electric field within the cables [54].

Magnetic field strength is measured in tesla (T) and is dependent on the current of the cable and distance. Magnetic field strength decreases with increasing distance from the source. For the high-voltage NordBalt subsea cable the magnetic field is shown in Figure 5.2. The magnetic field is 37 μT in very close vicinity and at a distance of 6 m from the cable there is almost no measureable magnetic field [55]. The distance at which no magnetic field is measured is only 2 m for the SwePol link [53]. For comparison the natural earth´s magnetic field is on average 50 μT.

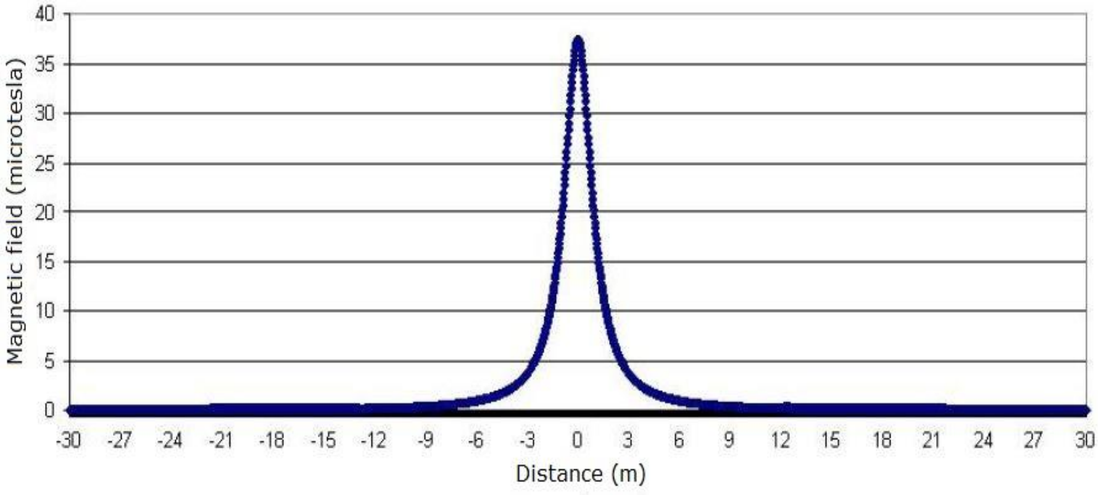

Figure 5.2 Changes in magnetic field of NordBalt cable depending on the distance from the cable [55].

There is no evidence found in literature that supports concerns about the effect that magnetic fields can have on marine species [53, 54]. If cables are laid within a distance of 10 m of each other, two peaks will be formed on the graph resulting in greater area affected by the magnetic fields. There is still concern about a mono-polar configuration because of the ground return, which is often the sea. The magnetic field can have a disturbing impact on ship compasses and magnetically controlled autopilots.

Chemical impact

Under normal operation subsea cables do not release any chemicals or other agents to the ambient. Solid cables such as extruded XLPE cables and mass-impregnated cables will not leak any fluid due to cable damage. The impregnation compound in mass-impregnated HVDC cables are of such high viscosity (thick) that it does not leak even if the cable is cut. Oil filled cables do leak oil if damaged as they are filled with low viscosity oil which is pressurized from an onshore feeder station. It can take days and even weeks to repair such a leak which can lead to bad environmental impact.

5.2 Summary

The environmental impact from a subsea cable during installation and operation is mostly due to the burying activity, temperature rise due to power losses in the conductor of the cable and the magnetic field. There is no proof that those impact or do harm to marine life and its surroundings. The environmental impact from subsea cable during installation and operation are negligible.

6 The Case of Iceland

6.1 Energy in Iceland

Iceland is a Nordic European island, situated in the North Atlantic, its area is 103,000 km2 and it has a population of about 322,000 inhabitants. Iceland is one of the most sparsely populated countries in Europe. The capital is Reykjavik and it is located in the south-western region of the country, 60% of the population lives in Reykjavik and the surrounding areas [9].

Iceland is located on both the Iceland hotspot and the mid-Atlantic Ridge, which runs right through it. This location means that the island is highly geologically active with many volcanoes and access to geothermal power and waterfalls. As shown in Figure 6.1 the Icelandic nation has been taking advantage of this and utilized those energy sources for electricity and district heating. Today most residents have access to inexpensive hot water, heating and electricity.

Iceland produces 85% of its domestic energy from renewable energy sources, hydro and geothermal power [8]. The utilization of the renewable energy sources in Iceland is constantly improving and Iceland has become one of the leading exporters of geothermal expertise even though electrical generation capacity in Iceland is small compared to other countries.

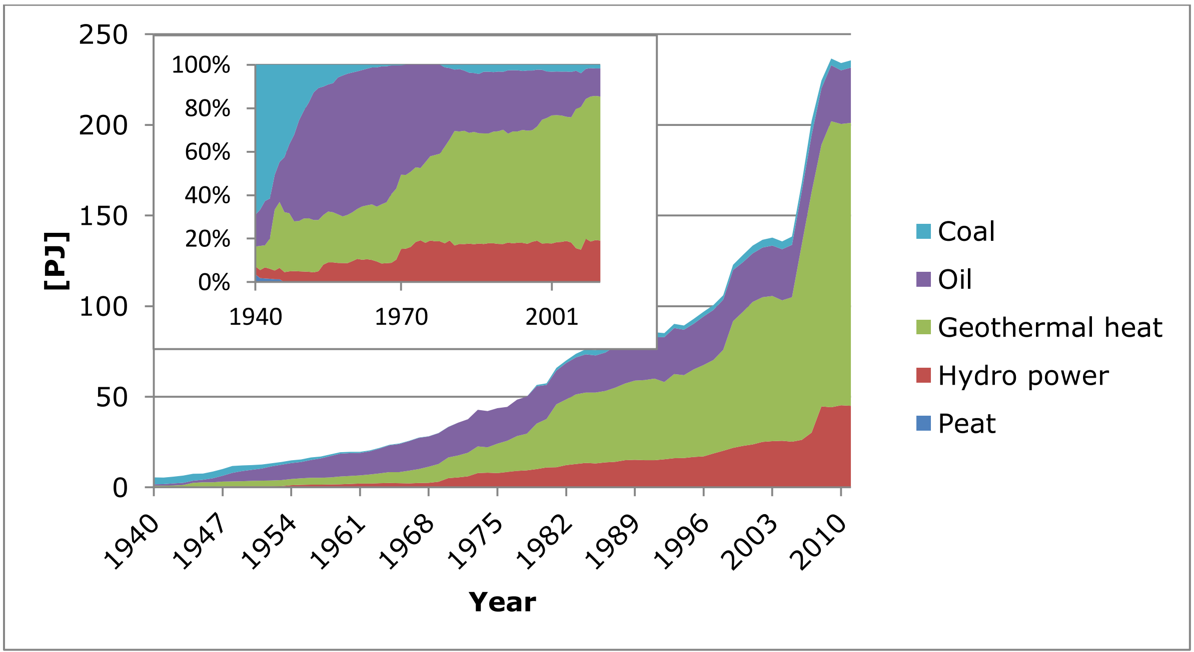

Figure 6.1 Primary energy source utilization (bigger graph) and proportion of each energy source (smaller graph) in Iceland, between 1940 and 2011 [8].

The information in Figure 6.1 about primary energy source utilization in Iceland is obtained from the National Energy Authority in Iceland [56]. There have been rapid changes in usage of energy sources in Iceland since 1940 with continuous increase in the use of renewable energy sources. There has especially been an increase in geothermal heat usage for district heating and electrical power generation. Only 15% of all energy consumed in Iceland is imported (fossil fuels), 90% of this is oil used for fishery and transportation.

Table 6.1 Total electrical power capacity of power plants in 2011 [8].

	MW	%
Hydro power	1.884	70,6
Geothermal heat	663	24,8
Fossil fuel	120	4,5
Total	2.668	100,0

Table 6.2 Electrical energy production in 2011 [8].

	GWh	%
Hydro power	12.507	72,7
Geothermal heat	4.701	27,3
Fossil fuel	2	0,0
Total	17.210	100,0

Table 6.1 and Table 6.2 show the total power capacity of all power plants and the energy production in Iceland in the year 2011, respectively. The amount of energy produced compared to primary energy utilization shows that 20% of all primary energy (hydro power) produces 70% of total energy capacity.

There are a total of 52 hydro power plants in Iceland and 7 geothermal power plants [8], generating on average 36 MW and 95 MW respectively. The eight biggest hydro power plants produce 90% of total hydro power capacity generated. The three biggest geothermal power plants produce almost 80% of total geothermal power capacity generated.

The electrical power system is a real-time electrical delivery system and does not store the energy, it produces what is consumed. The amount of produced and consumed energy is therefore estimated to be the same. Total power transmitted through the transmission system is around 2.050 MW with a maximum peak load of 2.200 MW [57], but total electrical power capacity of all power plants is 2.668 MW as seen in Table 6.1. That gives 400MW of excess electrical power. Fossil fuels are mostly used for reserve power and there must be, 10-15% of total electrical power capacity available as a reserve power [58].

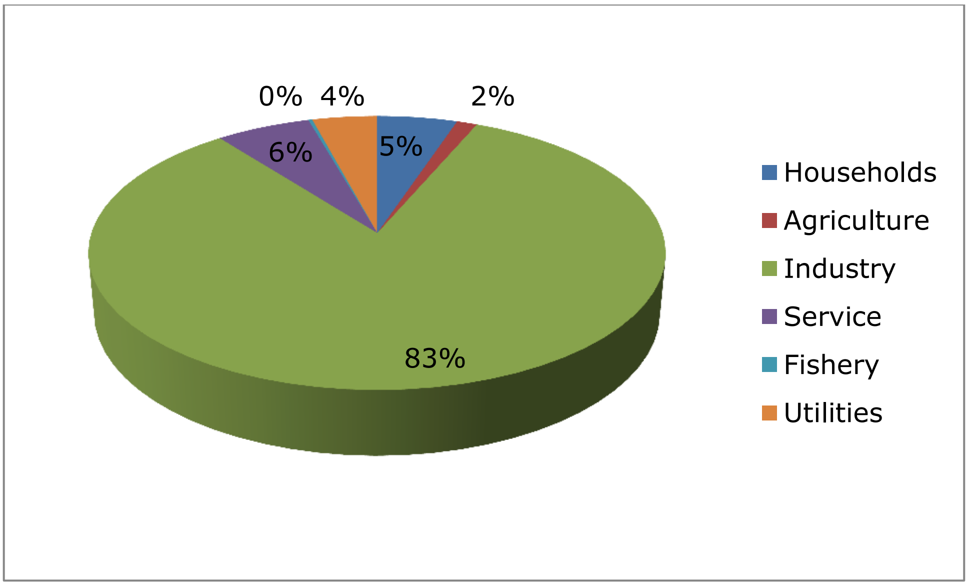

Figure 6.2 Energy consumption in Iceland 2011 [9].

Industry consumes a majority of the total energy demand in Iceland, or 83% as seen in Figure 6.2. Only 5% of energy consumption is by households.

6.1.1 Future Possible Electrical generation and demand

Although, Iceland has enormous amounts of energy, not all of the energy is or can be harnessed for electrical power generation. This is limited by both a legal framework and a regulatory governmental framework about utilization of hydro and geothermal energy sources [59]. The framework objectives are to evaluate the main energy sources in Iceland and simultaneously discuss their effect on nature, monuments and the environment, and the benefits of development early on, before spending too much and while there is still time to choose between ideas. The framework´s study on the effect on the environment can help energy companies to choose and evaluate their energy sources and locations and help them to see how the first idea can be changed to prevent adverse effects with little sacrifice in economy.

According to the framework, estimated annual additional generation of electrical power capacity is 17500 GWh and 30000 GWh for hydro power resources and geothermal heat resources, respectively. A total of 47500 GWh, or 5422 MW electrical power capacity generation is possible, but not all of this is available [59]. As only part of those resources are allowed to be utilized.

Proposed plans for future utilization of the energy sources in Iceland are a 630 MW aluminium factory at Helguvík in south Iceland and a 100 MW silicon factory located at Húsavík in north Iceland. Annual growth of electrical demand in Iceland is estimated at 50 GWh or 6 MW [8]. That adds up to 790 MW over the next 10 years which are not available today. To supply electricity to those projects further generation capacity is unavoidable.

Transmission through HVDC subsea power cables will be approximately 700 MW and requires even more generation. If a large portion of the possible additional electrical capacity is to be produced, it is important that the electrical transmission system in Iceland is able to withstand an increased capacity. That will be discussed in the next chapter.

6.2 The Electrical Transmission System

Iceland´s electrical transmission system is one electrical grid as represented in Figure 6.3. The transmission system is however isolated as it is not connected to any other country. Every power plant that produces more than 10,0 MW is required to connect to the transmission system, according to article nr. 5 of regulation on the implementation of electricity law. Landsnet hf., the Icelandic transmission system operator (TSO) owns and operates every main electrical transmission line in Iceland where the electrical energy is transmitted from power plants to distribution systems and large users. The transmission system includes 72 substations and approximately 3000 km of high-voltage transmission lines. The voltage rate is between 33 kV and 220 kV AC and there is no DC power transmitted in Iceland.

Reykjavik Energy, HS veitur, Norðurorka, Orkubú Vestfjarða, Rafveita Reyðarfjarðar and RARIK are the electricity distributors to households, companies and industry.

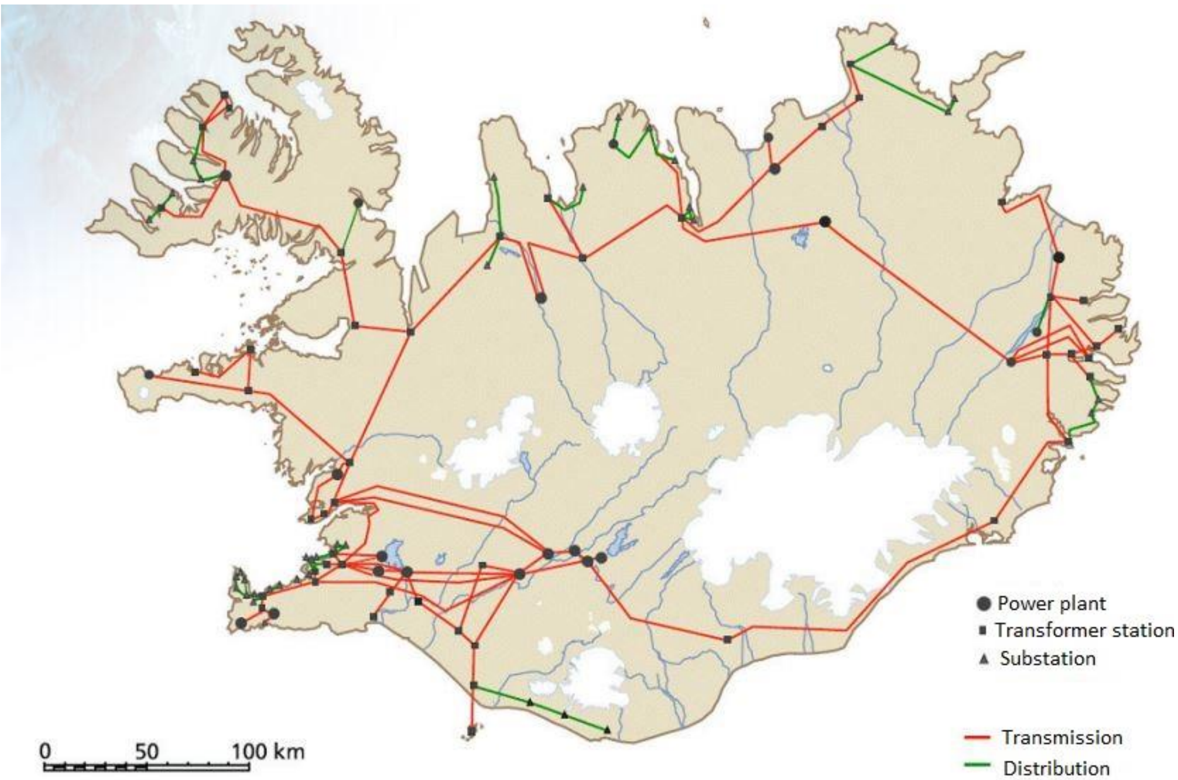

Figure 6.3 The transmission system in Iceland [8]

The total electrical power transmitted through the system is around 2050 MW. Industry consumes over 80% of that amount. Industry, especially the aluminium factories sometimes cause voltage fluctuations in the transmission system. A 500 MW load out of the system to one factory can cause fluctuations and decrease system stability. The transmission system today is not big or strong enough to withstand those loads without any effect on the system [58]. At present the system will not withstand 700 MW transmission through subsea cable.

Future strategy is to strengthen the system by 2050. There are e.g. plans to impose transmission lines across the highland. When the electrical transmission system has been strengthened, 500 MW loads will not have any influence on the system. Not even a subsea power cable [58].

Connection points discussed for the subsea cable system in Iceland are located at the east of Iceland. The cable link will be connected from a present delivery point in Iceland, passing the Faroe Islands then to Britain, as seen in Figure 6.4. The cable route is estimated at 1170 km and is assumed to reach a greatest depth of 1200m.

Figure 6.4 Possible HVDC subsea cable routes [60]

6.3 Icelandic experience

Around 1962 and 1978 subsea power cables were laid from mainland Iceland to the Icelandic island Vestmannaeyjar, located in the south of Iceland. The cable is now old and damaged and will not be functional in the foreseeable future and is therefore being replaced with a new one. The implementation of the new cable has started and is estimated to finish this year, 2013. The cable will transmit approximately 60 MW at 66 kV. The cable will replace an existing cable that is reaching the end of its operating lifetime. Installation of the new cable increases energy security to the island Vestamannaeyjar.

The 1978 cable was not laid according to the best possible route available at that time and was also not protected. The cable suffered a lot of damage and forced outages. To prevent that happening for the new cable a thorough marine survey was done to evaluate the route and the cable is protected by double armouring and will be buried in the sea bottom. Statnett, Norway´s TSO was a consultant for Landsnet hf for this project and ABB will manufacture the cable and install it. The cable will have an aluminium conductor solid core [58].

The new cable is not expected to be damage often and will cause fewer forced outages, only 2,2 hours/year. There is no contract with a repair vessel but if there is damage to the cable, Landsnet hf. will seek offers for a repair. It is estimated that repair can only take place in June, July and August due to high waves and bad weather conditions at other times of the year. For long outage duration, reserve diesel engines will have to supply electrical demand on the island [58].

6.4 Technological evaluation

The technological evaluation in this chapter of a subsea power cable system is based on the data available in Chapter 2 and 3.

The interconnection is evaluated to transmit 1000 MW of power through two single-core cables in a bi-polar configuration with emergency sea return to maintain half capacity during cable or pole outages. The interconnection is supposed to have the two poles completely independent of each other. Two single-core cables laid close to each other are also chosen to eliminate magnetic fields. The case for both cables suffering outage at same time is also evaluated.

The voltage rate 450-500 kV is evaluated as most suitable for Iceland´s conditions as the cable length will be very long and higher voltage rate results in lower power losses. The voltage rate of 450 kV is older technology and has good experience but recent technological breakthroughs of a 500 kV voltage rate for subsea power cable transmission has also had a positive service experience from the Italy-Greece link.

For a voltage rating of 320 kV there is a possibility of using extruded XLPE cable and IGBT transistors. It is argued that this configuration is better because of the mechanical and thermal properties of the cable, as discussed in Chapter 3.1. Because of a lack of sufficient data and experience of that specific configuration that solution is not chosen. CIGRÉ has enhanced working groups to provide information in the future about VSC converters. Currently, however the information collected and published is limited. According to the experience from Svenska Kraftnät [45] it is recommended to use mature technologies to increase reliability and extend the project life time. It is evaluated as very important to gain high reliability of the cable system because of possible long waits for a weather window if a cable is damaged.

The mass-impregnated cable type is chosen as it is a well-known and mature technology with great experience for interconnections over long distances and at great depth. It is the only alternative available today for the 400-450 kV voltage range.

The experience from the SAPEI link in Italy and research done prior to that installation recommends copper conductor for the shallower warmer parts and aluminium conductor for the deeper colder parts. Results from prior marine surveys on Icelandic bathymetry show there are about 430 km that is below 500 m in depth and that it reaches a greatest depth of 1200 m.

The HVDC system configuration in Table 6.3 is the configuration chosen for Icelandic conditions.

Table 6.3 Subsea power cable system configuration for Iceland

Configuration	Value
Power capacity (MW)	500x2
Voltage rate (kV)	450-500 kV
Cable type	Mass-impregnated
	Two, single core
Conductor	Cu and Al
	Bi-pole

Based on this evaluation on a subsea power cable system there is sufficient experience that contributes to the availability assessment that will be done in the following chapter.

6.5 Availability assessment for subsea cable

The experience from other similar projects regarding failure rate and availability is described in Chapter 4.8 and will be used to evaluate the availability of a cable in Icelandic conditions. Total availability for a subsea power cable is mainly due to forced outages, which are internal and external failures. Scheduled maintenance work on a subsea power cable is mostly limited to mechanical protection and can usually be performed with the cable in operation

In this assessment the internal and external failure rate will be estimated and the outage duration, or repair time. The mean time between failures will be estimated, both for internal and external failures and the total annual unavailability of the cable due to forced outages. A sensitivity analysis will be done on the cable availability as the waiting on weather window has significant impact on the cable availability.

6.5.1 Assessment of failure rate

Internal and external failure rate

With cleaner manufacturing and improved material, longer extrusion lengths and fewer joints the risk for internal damage is lower today than it was. Therefore it is estimated that the internal failure rate will be similar to the latest cable links failure rates. Using the data in Chapter 4.78 the internal and external estimated failure rate for the subsea cable from Iceland is given in Table 6.4.

In the estimation of external failure rate a suitable protection is assumed to be used along the whole route. Where there is not a possibility of burying the cable it will be protected with rock dumping. The armouring will also be very strong to withstand both laying forces and external violence.

A risk assessment for the NorNed subsea cable link estimated a failure rate of only 20% of the failure rate from real data as described in Chapter 4.8. The failure rate was estimated at 0,024 failures/year/100km and the reason for this was greater protection of the subsea power cable compared to many of the cables included in prior studies. The risk study indicated mean time between failures of 14 years for a 580 km long subsea cable. The availability of the NorNed cable in 2009 and 2010, as shown in Figure 4.2, is 93,0% and 74,6%, respectively which is mainly due to cable failure [43]. That is one failure a year.

The estimated failure rate for Icelandic conditions is 0,1 failure/year/100km.

Table 6.4 Estimated internal failure rate for the subsea cable from Iceland

	Internal failure rate	External failure rate
λ_{km} (failures/year/100km)	0,0044	0,100
λ (failures/year)	0,0471	1,070

The mean time between internal failures (MTBF) is estimated at 18 years.

The mean time between external failures (MTBF) is estimated at 1 year. The length of the cable influences the estimated failures per year. With longer length the risk of damage increases.

The outage duration for both internal and external failures is dependent on the weather and will be discussed below.

6.5.2 Outage duration and reliability

In the case of damage of a subsea cable, from Iceland to mainland Europe, the outage duration (MTTR) can vary significantly depending on project location and the weather conditions. By choosing a bipolar configuration, as recommended in Chapter 6.4, it is estimated that only one cable will be out at a time. For example, for an outage of one pole of a bi-pole system (50% loss of capacity) that lasted for two hours, the equivalent outage hours would be one hour. In a worst case scenario, both cables will be out of operation resulting in 100% loss of capacity for a certain duration. The damage is a dependent activity for both cables if they are laid close to each other. It could therefore be more appropriate to lay them along different routes to prevent them both being damaged by fishing activity, anchors or natural causes. The average time, without waiting on weather window (WOW), for a repair of subsea power cable damage is estimated at 40 days, as described in Chapter 4.7. The WOW time will be assessed by analysing sea state and wave height at two locations on possible routes from Iceland to mainland Europe in the North Atlantic Sea using data obtained from the Icelandic Maritime Administration which covers a 4 year period from 2009-2012. One location is near shore (coordinates 64 -14), approximately 50 km from the East coast of Iceland. The other location is far offshore (coordinates 62 -12,5) or approximately 400 km from the East coast of Iceland. The locations are shown with yellow dots on Figure 6.5. It is not only sufficient that the right weather window occurs, the duration should also be long enough to make sure that the repair can be carried out. Necessary weather window duration is estimated at seven days.

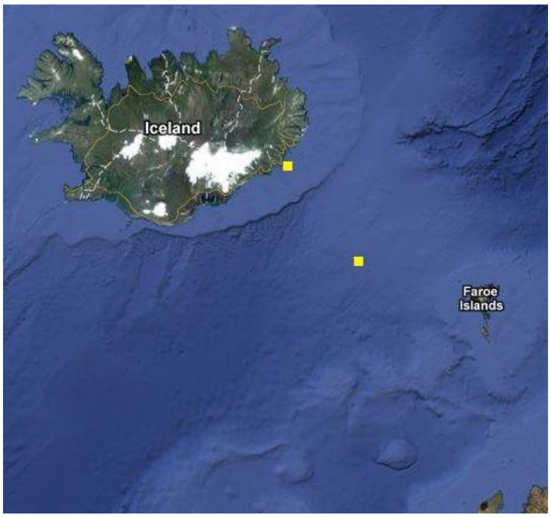

Figure 6.5 Locations for sea state data, the yellow dots [61]

Figure 6.6 shows the wave statistic near shore presented as a fraction of time for a wave height that is less than the value shown on the horizontal scale. Wave height near shore is < 3,5m 100% of the time during summer and 58% during winter.

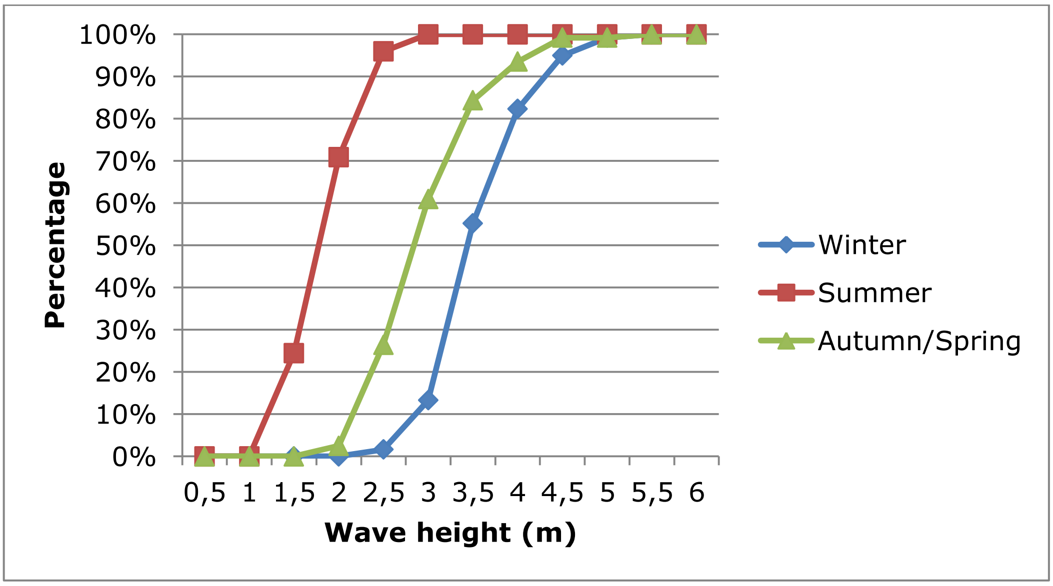

Figure 6.6 Fraction of time for sea state less than wave height, near shore

The waiting on weather window is shown in Table 6.5 at a location near shore. The weather window during the winter months (Nov., Dec., Jan., Feb.) is 54 days while during summer (May, Jun., Jul., Aug.) the wave height barely reaches 3,5 m. Therefore the waiting on weather time is low during summer.

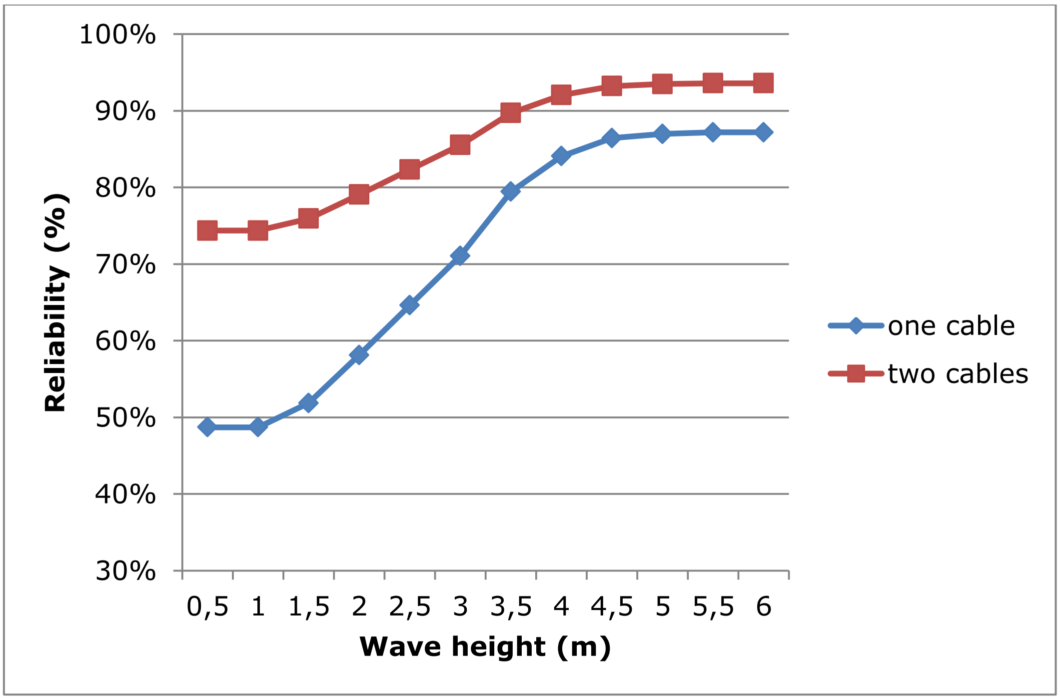

Figure 6.7 Reliability for single cable system and double cable system with different wave height limitation for repair activity, near shore.

In Figure 6.7 the reliability can be evaluated for different repair activity with different sea state limitations. The reliability for single and double cable systems is shown. For the system with two cables it is estimated that only one cable will suffer damage and will not be transmitting electricity. So there will only be a 50% loss in capacity. For one cable system there will be a 100% loss of capacity when the cable is damaged. In the case of a dependent damage action and both cables, in a two cable system, are not functioning, the reliability is the same as for one cable. For a sea state limitation of 3,5 m the reliability for a system with two cables where only one suffers outage, the reliability is estimated at 90%. For a single cable system, or both cables suffering outage in a double cable system, with sea state limitation of 3,5m the reliability is estimated at 79%.

Table 6.5 Waiting on weather for sea state limit 3,5 m, near shore

Winter	54 days
Summer	0 days
Autumn/Spring	18 days
Average	24 days

The waiting on weather window for repair activity that can only be performed with wave height less than 3,5 m are shown in Table 6.5. For a fault location near shore.

For a location far from land the waves are higher, as seen in Figure 6.8. Wave height far offshore is still < 3,5m 100% of the time during the summer period but only 15% of the time during winter.

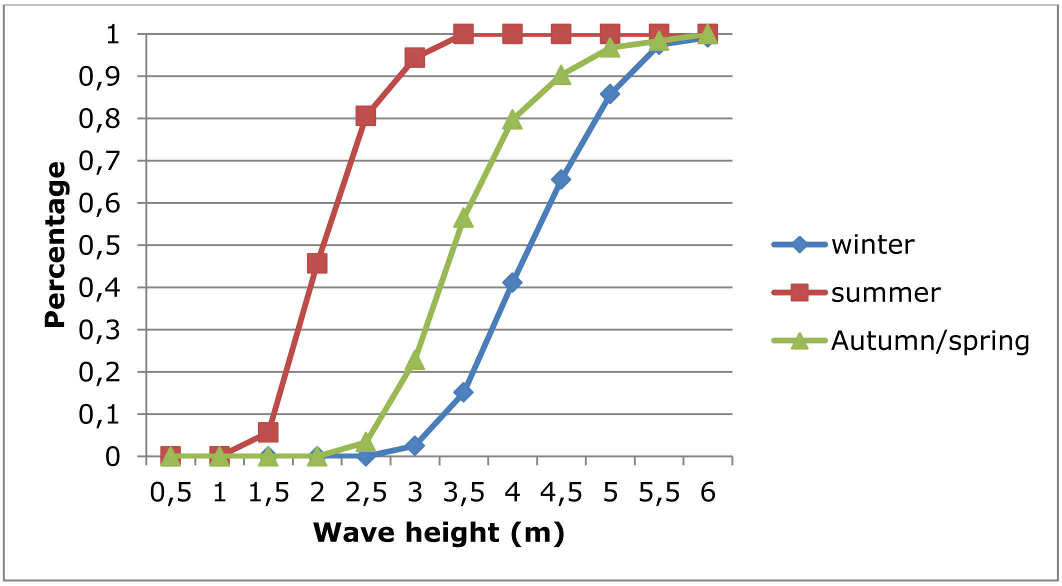

Figure 6.8 Fraction of time for sea state less than wave height, far offshore

Average wave height far offshore during winter time is 4,25 m and during summer time 2 m. In Table 6.6 the waiting on weather time for a far offshore location is shown. Repair availability is high during summer but there is only a small possibility of repair during winter time. The sea state is more harsh far offshore than near land which results in higher waiting on weather time during winter, autumn and spring (Mar., Apr., Sept., Oct.).

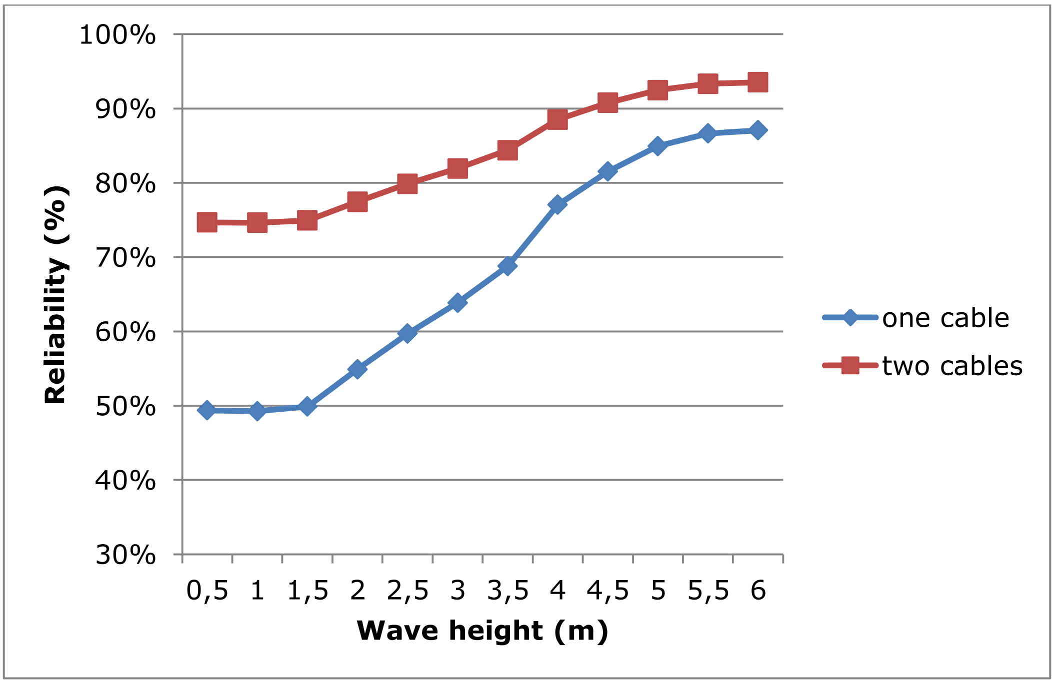

Figure 6.9 Reliability for single cable system and double cable system with different wave height limitation for repair activity, far offshore.

In Figure 6.9 the reliability for single and double cable systems can be evaluated for different repair activity with different sea state limitations. For the system with two cables it is estimated that only one cable will suffer damage and will not be transmitting electricity. So there will only be a 50% loss in capacity. For a one cable system there will be a 100% loss in capacity when the cable is damaged. In the case of a dependent damage action and both cables, in a two cable system, are not functioning, then the reliability is the same as for one cable. For a sea state limitation of 3,5 m the reliability for a cable system with two cables and only one suffers outage, is estimated at 84%. For a single cable system, or both cables suffering outage in a double cable system, with sea state limitation of 3,5m the reliability is estimated at 69%.

Table 6.6 Waiting on weather for sea state limit 3,5 m, far offshore

Winter	102 days
Summer	0 days
Autumn/Spring	52 days
Average	57 days

Table 6.6 shows the waiting on weather time for a sea state limit of 3,5 m with fault location far offshore.

For both locations there are short waiting on weather times during summer periods. There is however only a small possibility of repair to damaged subsea power cables far offshore during winter time.

Total duration and changes in unavailability with regard to location of the subsea power cable system is shown in Table 6.7.

Table 6.7 Average outage durations and unavailability of system with two cables

	WOW	Duration	Unavailability (%)
Near shore	24	64	10%
Far offshore	57	97	16%
Average	41	81	12%

Mean time before failure of 1 year results in average annual unavailability of 12% for the cable system. That is total outage of one pole or 50% loss of capacity for 78 days. It is assumed that the other cable is in service. For the possibility of both cables being out of function the unavailability increases and reaches 24% with a 100% loss of capacity during 156 days.

The sensitivity of the unavailability of one pole with regard to different duration with a failure rate (λ) of 0,1 failures/year/100km is shown in Figure 6.10.

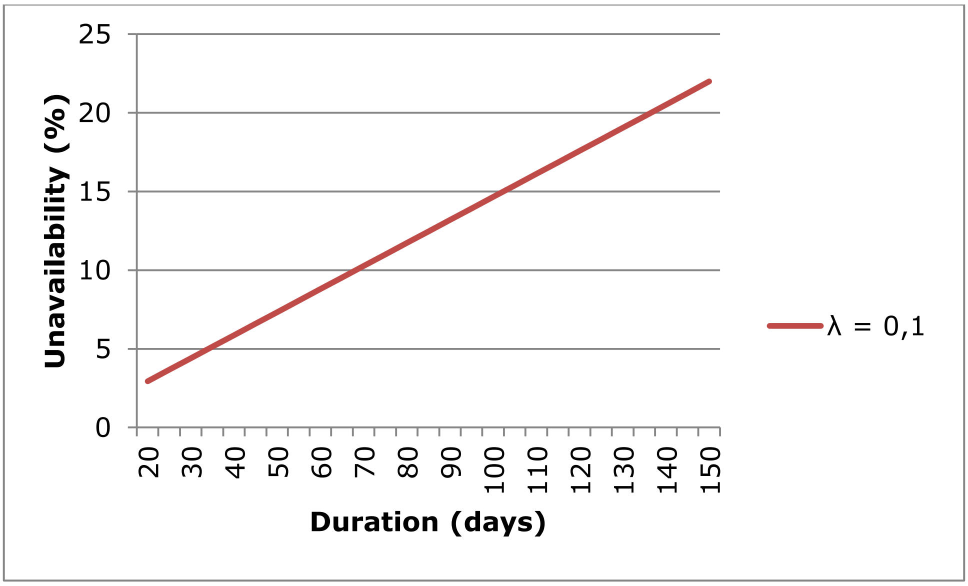

Figure 6.10 Sensitivy of subsea cable unavailability to different outage durations with λ expressed in failures/year/100km.

Figure 6.10 shows outage duration from 3 weeks to 5 months resulting in 3% and 22% unavailability, respectively; due to outage in one pole with the other pole working. For a repair near shore in good weather with available spare parts the duration could go down to 3 weeks. But for a fault location in open sea in harsh weather the outage duration could be 4 months resulting in 18% unavailability. It is recommended that spare parts are available as it can take several months to manufacture new cable which influences the availability of the asset. For the case of both cables suffering outage, or the cable in a one cable system, the unavailability doubles in percentage.

Experience tells us that there is less probability for damage to occur at greater depth. Far offshore the depth is greater and estimating a 30% probability of a damage occurring far offshore and 70% near shore the outage duration and unavailability changes as shown in Table 6.8.

Table 6.8 Outage duration and unavailability

	WOW	Duration	Unavailability (%)
Average	32	73	10%

This implies that the unavailability of the subsea cable due to damages is closer to 10%.

6.6 Summary

Iceland has an enormous amount of renewable energy and could be a good candidate for transporting renewable energy through subsea cable to mainland Europe. For that to happen there needs to be further electrical generation and strengthening of the transmission system. The transmission system will be fully strengthened in 2050 to withstand additional required load, according to Landsnet hf. The transmission system in 2050 will also withstand interconnection of subsea cable. The impact on the transmission system from the cable project is therefore dependent on the timing, if the project will be implemented.

There seems to be no limitation for the subsea cable technology. The technology is estimated to be suitable for Icelandic conditions. The length and depth of the cable route are a challenge for design and installation, but experience tells us that this is probably technologically feasible. The technology suggested for Icelandic conditions according to state-of-the-art is mass-impregnated cable with double wire armouring using copper conductor for the shallow ends and aluminium for the deepest part. To eliminate magnetic field two single-core cables are most suitable laid side by side and to improve reliability a bi-polar configuration is recommended. With bi-polar configuration one cable can be in operation while the other is out of service for repair. It is also of the utmost importance to protect the cable from anchors and other external violence by burying it under the seafloor. With the fast growing development in technology it is important to follow up on the latest technology. The environmental impact from recommended subsea cable does not threaten surrounding areas or marine life.

Icelandic weather conditions influence the reliability of the cable system significantly. In relation to the Vestmannaeyjar cable link it is assumed that no repair can be done for the majority of the year, or only in June, July and August. High reliability of the subsea cable from Iceland to mainland Europe is therefore very important. The failure rate for mass-impregnated cables are 0,1 failure/year/100 km which results in one failure a year for subsea cable from Iceland to mainland Europe. For an average outage period of 78 days, or almost three and a half months, the annual unavailability is 12%. With less probability of damage at greater depth the fraction is less than the average unavailability.

7 Discussion and Summary

There has been great evaluation in implementations of HVDC subsea power cables. With increased social consciousness about global warming and climate change, renewable energy source utilization has risen with subsea power cable interconnections. There are high-voltage transmission highways forming around Europe, and other continents, creating a flexible energy source mix with better utilization of renewable energy sources.

7.1 Technology

The need for increased renewable energy source utilization has forced the technology forward. Challenges are constantly confronted with new developments in technology. The development in material and manufacturing processes has increased power capacity and voltage rating and made the cables more robust. The cable systems are frequently being laid at greater depth and over longer distances. The maximum power capacity is 800 MW (single cable) at 500 kV or 1000 MW (two cables) at 320 kV, for mass-impregnated cables and extruded XLPE cables, respectively.

The key factors to a successful HVDC subsea power cable project is a thorough marine survey to find the most suitable route and for design of the cable. Great expertise in installation method is also crucial, concerning choice of vessel, equipment and crew.

7.2 Reliability

Savings in investment cost, which could lower the reliability of the cable system, could result in higher operation and repair cost in the future. When a cable is damaged and is in need of repair, there is always need for a specialised vessel, equipment and crew. That is independent on the size of the damage and could therefore be a big part of the repair. The time waiting for weather can also be very expensive. Additionally there is loss in revenues when no power is transmitted. Those considerations must be optimized during planning and designing of a cable project.

With prior experience and development of subsea cable systems the reliability has improved. From 1986 to 2009 the reliability has improved from 0,264 failures/year/100km to 0,100 failures/year/100km. Operation procedures with real-time monitoring improve maintenance of the system which can prevent major damage to occurring, resulting in better reliability and longer life time of the system.

7.3 Environmental impact

When implementing such a large complex electrical system there are always concerns about the environmental impact. According to the latest researcher and environmental impact assessments in Sweden there are no threats to the surrounding area and it will not suffer permanent damage, from installation and operation of the cable. Latest technological developments have decreased the electrical magnetic field and improved installation methods. The magnetic field is so low that sensitive marine life and ship compasses have not been influenced in a bad way, according to the latest research.

7.4 The case of Iceland

The cable route from Iceland to mainland Europe will lay under the North Atlantic Ocean passing the Faroe Islands and will be approximately 1170 km long and reach a depth of 1200m. The suitable technology for Icelandic conditions is two mass-impregnated single-core cables, each transmitting 500 MW at 400-450 kV in a bi-polar configuration. That solution improves reliability and eliminates magnetic fields. It is recommended to have copper conductor at the shallower parts and aluminium for the deeper colder part because of the increased laying tensions. Cable burial of at least 2 m is recommended for the whole route to protect against external violence where possible.

The failure rate for the subsea cable between Iceland and mainland Europe is estimated at 0,1 failure/year/100 km which results in 1 failure a year. The outage duration for each repair is dependent on fault location and weather conditions. For a fault location near shore there is more accessibility of weather window which reduces outage duration. The outage duration is higher far offshore but there is also less probability of damage as the cable will be laid at great depth. The availability on the subsea cable is variable between seasons and locations. During winter the access to repair is less than during other seasons. The average unavailability of the system due to damage is estimated at 12% but with less probability of damage at great depth the unavailability is less, or near 10%.

If sensitive marine species can be avoided along the cable route, the environmental impact is estimated to be low. There is no relation between magnetic fields of HVDC subsea cables and threat to marine life and with the cable type recommended there is no danger of chemical impact, or oil leakage. By laying the cables close together the magnetic fields can be eliminated. Landmarks on the sea bottom formed during cable burial is said to recover in approximately one year.

Taking into account the proposed utilization by aluminium and silicon factories there is a need for greater utilization of energy sources for electrical generation. With additional electrical power needed for subsea power cables even more energy sources will need to be utilized for generation. With regards to the transmission system it is only a matter of time until the cable will have an affect. In 2050 it is estimated that the transmission will withstand future demand of electricity.

7.5 Future work

Developments in technology are of special interest. Future technology like superconductors and advanced maintenance tools being developed will increase power capacity and minimize duration of outages, resulting in more asset feasibility. Also the expected future development of extruded XLPE cables

Possible future projects could consist of more specific analysis of the sea state to evaluate suitable routes based on reliability of different locations and to collect real operation data from the owners and operators of the HVDC subsea cable systems.

This thesis can help in the evaluation of a new subsea cable link. The aspects considered are the latest developments and are important to include for a successful project. It is also important to keep in mind that technology develops quickly and any publications might be out of date when read in several years. It is important to follow up on state-of-the-art when evaluating and operating such a large technical system.

References

1. Franco A. Startegies for optimal penetration of intermittent renewables in complex energy systems based on techno-operational objectives. Renewable energy. 2011;26:743-753.
2. Erdinc O. Optimum design of hybrid renewable energy systems: Overview of different approaches. Renewable and Sustainable Energy Review. 2012.
3. Hein KRG. Future energy supply in Europe - challenge and changes. Fuel. 2005;84(10):1189-1194.
4. Bayliss CR, Hardy BJ. High voltage direct current transmission. In: Transmission and Distribution Electrical Engineering. 4th ed. London: Newnes, 2012; p.1027-1057.
5. European commission. Effort of Member States to reduce the greenhouse gas emissions to meet the Community´s greenhouse gas emission reduction commitments up to 2020. 406/2009/EC2008.
6. British Petroleum. BP Statistical Review of World Energy June 2012 [serial online]. c2012[cited 2013 feb 14]. Available from: http://bp.com
7. Park S. Iceland´s hydrogen energy policy development (1998-2007) from sociotechnical experiment viewpoint. Hydrogen Energy. 2011;36:10443-10454.
8. National energy authority. Energy statistics [homepage on the internet]. c2013 [updated 2013 Jan 13; cited 2013 Feb 2] Available from: http://www.os.is/ /yfirflokkur/raforkutolfraedi/.
9. Statistic Institute of Iceland. Energy statistics [homepage on the internet]. c2013 [updated 2013 Jan 13 ; cited 2013 Feb 17] Available from: http://www.hagstofa.is/Hagtolur/Idnadur-og-orkumal/Orkumal
10. Blume SW. Electric Power System Basics. New Jersey: A John Wiley & Sons; 2007.
11. Summerton J. Changing large technical tystems. Colorado USA and Oxford UK: Westview press; 1994.
12. ENTSOE. European network of transmission operators of electricity [serial online]. c2009[cited 2013 Mar 23] Available from: www.entsoe.eu.
13. Nord Pool Spot. Electrical power market data [homepage on the internet]. c1996 [updated 2013 Mar 23 ; cited 2013 Mar 23] Available from: http://www.nordpoolspot.com/.
14. Rashid MH, editor. Power Electronic Handbook. 3rd ed. Burlington, USA: Butterworth-Heinemann; 2011.
15. Kirtley JI. Electric Power Principles : Sources, Conversion, Distribution and Use. NJ, USA: Wiley; 2010.
16. Benatio R, Forzan M, Marelli M, Orini A, Zaccone E. Harmonic behaviour of HVDC cables. Electric power system research. 2012;89:215-222.
17. Hanley TL, Burford RP, Fleming RJ, Barber KW. A general review of polymeric insulation for use in HVDC cables. IEEE Electrical insulation magazine. 2003;19(1):13-24.
18. Hammons TJ. Power cables in the twenty first century. Electric power components and systems. 2003;31(10):967-994.
19. Worzyk T. Submarine power cables and their design elements. In: Submarine Power Cables: Design, installation, repair, environmental aspects. Berlin: Springer-Verlag Berlin Heidelberg; 2009, p.9-50.

20. Reddy CC. Theoretical maximum limits on power-handling capacity of HVDC cables. IEEE Transaction on Power Delivery. 2009;24(3):980-987.
21. Worzyk T. Design. In: Submarine Power Cables: Design, installation, repair, environmental aspects. Berlin: Springer-Verlag Berlin Heidelberg; 2009, p.51-104
22. Reddy C, Ramu TS. Estimation of thermal breakdown voltage of HVDC cables - a theoretical framework. IEEE Transaction on Power Delivery. 2007;14(2):400-408.
23. Feld G, Owen DG, Reuben RL, Crockett AE. Mechanical behaviour of the metallic elements of submarine cables as a function of cable loading. Engineering structures. 1995;17(4):240-253.
24. Nakamura M, Nanayakkara N, Hatazaki H, Tsuji K. Reliability analysis of submarine power cables and determination of external mechanical protections. IEEE Transaction on Power Delivery. 1992;7(2):895-902.
25. Guerin P, Giam H, Ai B, Destrual P, Deschamps L, Perret J. Pressure and temperature dependence of the dielectric breakdown of polyethylene used in submarine power cables. Journal of Applied Physics. 1985;57(10):4805-4807.
26. IEEE. Existing HVDC projects listing. IEEE [homepage on the internet], c2012 [updated Mar 1; cited 2013 Mar 3]. Available from http:// http://www.ece.uidaho.edu/hvdcfacts/Projects/HVDCProjectsListingMarch2012-existing.pdf
27. ABB. Submarine power cables [homepage on the internet]. c1988 [updated 2013 Apr 2; cited 2013 Apr.2]. Available from: http://www.abb.com.
28. Larsen B. Performance of the 250 kV HVDC Skagerrak submarine cables. Further development of the HVDC paper-insulated, mass-impregnated (Solid type) submarine cable. IEEE Transaction on Power Delivery. 1988;3(1):1-15.
29. Verbruggen A, Marchohi MA. Views on peak oil and its relation to climate change policy. Energy Policy. 2010;38:5572-5581.
30. International energy agency. Nordic Energy Technology Perspective. Pathways to a Carbon Neutral Energy Future. 2013.
31. IEEE. IEEE guide for the planning, design, installation and repair of submarine power cables. IEEE, 2004 Contract No.: IEEE Std 1120-2004.
32. CIGRÉ. NorNed - World´s longest power cable. France: CIGRÉ, 2010 CIGRÉ publication B1_106_2010.
33. Chen G, Zhao J, Li S, Zhong L. Origin of thickness dependent dc electrical breakdown in dielectrics. Applied physics letter. 2012;100(22):2229041-2229044.
34. ABB. HVDC light cable [homepage on internet]. c1988 [updated 2013 Apr 2; cited 2013 Apr 2]. Available from: http://www.abb.com/industries/db0003db004333/add2081b520d929ac12574810034c0c4.aspx.
35. ABB. Cables and cable asseccories [homepage on interent]. c1988 [updated 2013 Apr 2; cited 2013 Apr 2]. Available from: http://www.abb.com/cables.
36. ABB. Environmental impact and design of submarine cables [email]. 2013.
37. CIGRÉ. Qualification test program for the 1000 MW - 500 kV HVDC very-deep water submarine cable interconnection between Sardinia island and Italian Peninsula (SA.PE.I). France: CIGRÉ, 2008 CIGRÉ publication B1-101.
38. CIGRÉ. 2010 general report group B1 (Insulated cables). France: Cigré, 2010.
39. CIGRÉ. 2008 general report group B1 (Insulated cables). France: Cigré, 2008.
40. Worzyk T. Accessories. In: Submarine Power Cables: Design, installation, repair, environmental aspects. Berlin: Springer-Verlag Berlin Heidelberg, 2009, p.105-121.

41. Worzyk T. Installation and protection of the submarine power cables. In: Submarine Power Cables: Design, installation, repair, environmental aspects. Berlin: Springer-Verlag Berlin Heidelberg, 2009, p.161-209.
42. Worzyk T. Operation and Maintenance. In: Submarine Power Cables: Design, installation, repair, environmental aspects Berlin: Springer-Verlag Berlin Heidelberg, 2009, p.237-247.
43. CIGRÉ. A survey of the reliability of HVDC systems throughout the world during 2009-2010. France: CIGRÉ, 2012 publication B4-113.
44. CIGRÉ. Update on Service Experience for HV underground and submarine cable systems. France: CIGRÉ, 2009 publicaton 379.
45. Svenska Kraftnät. Operation and failure statistics [email]. 2013.
46. Bayliss C, Hardy BJ. Distribution planning. In: Transmission and Distribution Electrical Engineering. 4th ed. London: Newnes, 2012.
47. CIGRÉ. Third-party damage to underground submarine cables. France: CIGRÉ, 2009 publication 398.
48. Worzyk T. Damages and repair. In: Submarine Power Cables: Design, installation, repair, environmental aspects. Berlin: Springer-Verlag Berlin Heidelberg, 2009 p.211-236.
49. CIGRÉ. Reliability and damages [email]. 2013.
50. Hovland E, Gudmestad OT. Selection of support vessel for offshore operations in hars environments. exploration & production. 2008;6(11):52-57.
51. O´Connor M. Weather window analysis of Irish west coast wave data with relevance to operations & maintenance of marine renewables. Renewable energy. 2013;52:57-66.
52. Stromme. RAM for NorNed cable HVDC project. 1998.
53. Andrulewics E. The environmental effects of the installation and functioning of the submarine SwePol Link HVDC transmission line: a case study of the Polish Marine Area of the Baltic Sea. Journal of Sea Reasearch. 2003;49:337-345.
54. Worzyk T. Environmental issues. In: Submarine Power Cables: Design, installation, repair, environmental aspects. Berlin: Springer-Verlag Berlin Heidelberg, 2009 p.249-268.
55. Svenska Kraftnät. Vattenverksamhet för förläggning av sjökabel inom projekt NordBalt. Miljökonsekvensbeskrivning. Sweden: Svenska Kraftnät, 2012.
56. National energy authority in Iceland. Orkustofnun Íslands.
57. Icelandic transmission system operator, Landsnet [homapage on internet]. Transmission system c2013 [updated 2013 Apr 23; cited 2013 Apr 23]. Available from: www.landsnet.is.
58. Icelandic transmission system operator, Landsnet [email]. Transmission system operation. 2013.
59. Rammaáætlun. Virkjunarkostir í 2. áfanga. 2012.
60. Landsvirkjun [homepage on internet]. Energy data c2013 [updated 2013 Apr 25; cited 2013 Apr 25] Available from: www.landsvirkjun.is.
61. Administration. Icelandic Maritiem Administration [homepage on internet]. Sea state data c2013 [updated 2013 May 3; cited 2013 May 3] Available from: www.sigling.is.