CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF ELECTRICAL ENGINEERING
DEPARTMENT OF ECONOMICS, MANAGEMENT AND HUMANITIES

MASTER THESIS

FEASIBILITY STUDY TO IMPLEMENT AN HIGH VOLTAGE DIRECT CURRENT TRANSMISSION LINK

STUDY PROGRAM: ELECTRICAL ENGINEERING, POWER ENGINEERING AND MANAGEMENT
FIELD OF STUDY: ECONOMICS AND MANAGEMENT OF POWER ENGINEERING
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PRAGUE 2017

ZADÁNÍ DIPLOMOVÉ PRÁCE

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

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Studijní program: **Elektrotechnika, energetika a management**

Studijní obor: **Ekonomika a řízení energetiky**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

FEASIBILITY STUDY TO IMPLEMENT AN HIGH VOLTAGE DIRECT CURRENT TRANSMISSION LINK

Název diplomové práce anglicky:

FEASIBILITY STUDY TO IMPLEMENT AN HIGH VOLTAGE DIRECT CURRENT TRANSMISSION LINK

Pokyny pro vypracování:

- literature research for HVDC transmission
- quantify the need to strengthen the German Transmission Grids (Südlinks)
- design variants in HVDC through the Czech Republic
- comparison between designed variants and German proposals from the economic point of view

Seznam doporučené literatury:

PADIYAR, K. HVDC Power Transmission Systems: Technology and System Interactions. New Delhi: New Age International (P) Limited, Publishers, 2015.
JOCVIC, D., AHMED, K. High Voltage Direct Current Transmission: Converters, Systems and DC Grids. United Kingdom: John Wiley & Sons, Ltd, 2015.

Jméno a pracoviště vedoucí(ho) diplomové práce:

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Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

Datum zadání diplomové práce: **17.02.2017** Termín odevzdání diplomové práce: ____________

Platnost zadání diplomové práce: ____________

Podpis vedoucí(ho) práce Podpis vedoucí(ho) ústavu/katedry Podpis děkana(ky)

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DECLARATION

I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague".

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ABSTRACT

The purpose of this thesis is to provide comprehensive information of HDVC transmission and to suggest a study to implement an HVDC link. The first part of the thesis provides a basic description of the technology, advantages, and disadvantages related to the dc transmission of electrical energy. The thesis also shows a basic proposed design model of HVDC link with different variants. The calculations of general parameters and estimated cost are presented. Subsequently, the variants are compared against them.

KEYWORDS HVDC, bipolar, converter, direct current, point-to-point, transmission network

CONTENT

LIST OF ABBREVIATIONS

AC		Alternative Current
AN		Audible Noise
ASEA	Allmänna Svenska Elektriska Aktiebolaget	General Swedish Electric Company
HVDC		High Voltage Direct Current
CSC		Current-Sourced Converter
DC		Direct Current
EXP		Expenditure
GE		General Electric Company
IGCT		Integrated Gate-Commuted Thyristor
LCC		Line-Commutated Converter
NPC		Net Present Cost
NPV		Net Present Value
OHL		Overhead Line
O&M		Operating and Maintenance
RF		Radio Frequency
RI		Radio Interference
ROW		Right of Way
TSO		Transmission System Operator
TYNP		Ten-Year Network Development Plan
VSC		Voltage-Source Converter
WACC		Weighted Average Capital Cost

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INTRODUCTION

The increase of the electricity demand; the integration of new generating capacity, mainly as renewable energies; and depreciation of transmission assets result in the need for the expansion of transmission networks. In addition to these needs, the integration of the European electricity market also plays a vital role in the network expansion plans to meet the needs of cross-border interconnection capacities.

However, it is important to note that it may be the case where a country's network expansion plans are focused on national benefits and that these may not coincide with adequacy plans for cross-border investments to increase capacity and so to raise the volume of trade. But, there is a need for planning at the regional level in order to achieve the goals proposed by the European Union.

An important step in meeting the needs for a long-term European network development plan is the Ten-Year Network Development Plan (TYNDP) of ENTSO-E. This plan takes national plans into account and incorporates regional aspects. According to TYNDP 2014, around 100 bottlenecks were identified in the European transmission network, which will require new investments to improve it. Annex A shows the locations where they will occur because existing structures will not be able to transfer power flows. In order to eliminate these bottlenecks, different national projects and projects of common interest have been studied and proposed.

In a particular case, the congestion between northern Germany (where there is huge wind power supply) and south Germany (where nuclear power has been shut down) is generating unplanned flows through the transmission systems in Central Western Europe and Central Eastern Europe. These spontaneous flows overload internal networks and increasingly affect trading capacities. Thus, the increasing importance of renewable energies poses new demands on electricity transmission and distribution networks. For instance, the transport of large amounts of electricity generated in low-consumptions regions or remote areas, through long distances to the consumption centers. As a result, several hundred kilometers of power transmission lines must be upgraded, while others must be built.

These investments in transmission are costly, irreversible and long term, therefore, they must be planned and justified. For example, an overinvestment in transmission assets leads to a reduction in cost-efficiency for electricity supply. However, a lack of investment leads to a decrease in the reliability of the system and limits the integration of large proportions of renewable energies into the system. Then, it is necessary to find an optimum and feasible investment level for the expansion of the transmission networks.

Germany has opted for HVDC technology for large projects, due to its applicability and great advantages when talking about bulk transmission of power over long distance, among others. Links are being planned between the north and south of the Germany known as Südlinks. These new high-voltage lines are very important especially for the south of the country, as it will ensure the security of supply of electricity throughout the region.

For all of the above exposed, it has been considered as a case study of this thesis to analyze the possibility of an HVDC link between Germany and Austria through the Czech Republic. On a first stage a point-to-point HVDC link between substations in Röhrsdorf, Germany and Dürnrohr, Austria. The objective is to carry out a feasibility study of a link of this type and compare it with different proposals.

This thesis will start with outlining the basic characteristics of high voltage direct current transmission, the background information focusing on the technical aspects, performance, limitations and requirements for environmental and economic conditions. Chapter 2 contains a brief description of the status of German transmission network and plans for additional transmission infrastructure focusing in the Südlinks. Chapters 3 and 4 are the focus of the project, as they describe the characteristics, assumptions, design considerations and the comparative economic analysis for the different variants on the considered link. Finally, the conclusions drawn from the project are presented.

1. OVERVIEW OF HIGH VOLTAGE DIRECT CURRENT TRANSMISSION

1.1. HIGHLIGHTS OF HVDC TECHNOLOGY

The history of the high voltage direct current technology began with the War of Currents at the end of the nineteenth century. At that time, Thomas Alva Edison reached significant achievements using DC technology like the commercial dynamo and the incandescent lamp in 1879 and then, the delivering of electrical energy to New York´s financial district through the Pearl Street Station in 1882 [1].

The electric era had started using direct current, but its dominance was brief; because George Westinghouse, Nikola Tesla, and others were joined to take advantage of the performance improvements of transformers and induction motors, which produced that AC generation, transmission, and utilization were dominant.

But getting back to the development of DC technology, one of the first challenges was the transformation of DC voltage to higher or lower voltage levels; many methods were applied like mechanical means and plasma devices. However, the creation of the needed switching equipment was difficult because the devices could not resist high voltages. Dr. Uno Lamm, known as the Father of HVDC, around 1929 had designed and obtained a patent on a converter valve capable of resisting the conditions [29, 30, 31]. But, before a practical converter valve based on Dr. Lamm's design could be constructed, they had to spend almost 15 years to solve other technical problems associated with materials and manufacturing.

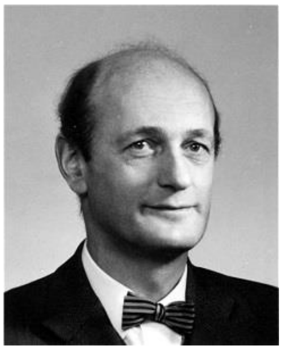


FIGURE 1: DR. UNO LAMM [31].

In the 1930s for the most part, the earliest research efforts about HVDC converter technology were made. There were also presented many papers related to converter technologies, the economics of DC transmission systems, configurations and topologies, insulation systems, feasibility and even demonstration systems by researchers from Sweden, Germany, Russia, United States and France [29].

The 1940s was a decade where the interest in HVDC continued. The emphasis shifted to issues like aspects of transmission systems DC through overhead lines and cables; ground return research; laboratories for testing and demonstration of feasibility. By 1945, the Swedish State Power Board and ASEA built a test line of 50 km between Trollhättan and Mellerud in Sweden and a valve testing center in Trollhättan [30]. With this test line, ASEA gained experience primarily with the conversion technology that would later be utilized for the design of various valves.

The development of HVDC technology was accelerated throughout the 1950s; literature was developed in a deeper sense and covered topics such as physical simulators for the design of DC systems; modeling of equipment and radio interference from converters were included [29].

By 1950, the State Power Board placed the first commercial order with ASEA for an HVDC system, a submarine cable with a capacity of 20 MW at 100 kV connecting the mainland of Sweden and the island of Gotland. The system design was led by Erich Uhlmann, while Harry Forsell aided with the control system design [29]. One of the particular requirements of this system was that it should be able to provide the island with power in the absence of any local generation because Gotland had almost no local generation. Therefore, a synchronous condenser of 30 MVA was installed at the inverter station in Gotland. The Gotland HVDC link was in many aspects more complex than other current systems in the world nowadays, and it came into service in March of 1954 [29].

In 1957, ASEA received the second commercial order for a system of 160 MW at $\pm$ 100 kV that would connect England and France [29]. This project known as the Cross Channel or the English Channel came into service in 1961, was developed in favorable conditions and served to learn about the harmonic instability that can happen in these systems and how to deal with them through the control system.

After the Cross Channel project, several HVDC transmissions using mercury-arc valves were built during the 1960’s [29, 30]. These were:

- The Konti–Skan project was a link of 250 MW at 250 kV between Sweden and Denmark established in 1965, to sell surplus hydro energy to Denmark and to provide peak support to the Nordic system when needed [32, 33].
- The New Zealand project was a system of 600 MW at $\pm$250 kV between the Benmore Station on New Zealand’s south island and the Haywards substation on the north side, which came into service in1965. This system combined 575 km of overhead lines and 42 km of an undersea cable under Cook Strait [32, 34].
- The Sakuma project was a system of 300 MW, 2×125 kV, back-to-back. It was the first HVDC frequency converter to connect the 50 and 60 Hz systems in Japan [32].
- SACOI Link was a DC project of 200 MW at 200 kV undersea cable link between Sardinia and the Italian mainland that was commissioned in 1967[35].

Over time, ASEA realized that it could not remain as the exclusive supplier of HVDC technology and consequently signed license contracts with English Electric and General Electric Company [32].

The following major technology innovation was applied in the Pacific HVDC Intertie connecting the Columbia River and Los Angeles in the USA. This bipolar OHL project of 1,440MW at $\pm$400 kV was developed by ASEA and General Electric and commissioned in 1970 [36]. Among the most remarkable features of this system were that it was the first HVDC line designed to be embedded in an AC network; it was originally conceived as a multiterminal system; and it was probably the world’s first transmission system controlled by means of a distributed computer system configured as a multiprocessor, multitasking real-time control system [29, 32].

The solid–state thyristor took over from the mercury arc valves beginning in the late 1970s. General Electric designed powerful thyristors and became a viable supplier of HVDC systems using thyristor valves. However, ASEA was able to make the transition from the mercury arc valves to the thyristor technology through a license from GE, and also emerge as a leader of this technology [32].

Even when ASEA was the first to demonstrate this new valve technology, the system of Eel River 320 MW, back-to-back at 2×80 kV, established in 1972 by GE, was the first all-solid-state converter system in operation [37]. Then, companies like English Electric, BBC, Siemens, Hitachi, Toshiba, and Mitsubishi supplied converter systems based on solid-state converter valves.

The next period in HVDC transmission involved multiterminal systems. Here, the most significant achievements that can be mentioned are the addition of a 50 MW converter station on the island of Corsica for tapping the Sardinia to the Italian mainland HVDC submarine link by GE; and the multiterminal parallel bipoles system of Nelson River [38].

Later, from 1984 through 1987, came into operation in stages the Itaipu project, which is considered as the major technology leap and one of the largest HVDC transmissions in the world. The system of 3,150 MW at ±600-kV is about 800 km of OHL, and connects the hydropower generation from Foz do Iguacu to Sao Paulo in Brazil [39].

The continuous development of the technology brought down the losses; increased the transmission voltages, and added new elements such as active AC and DC filters [22]. Furthermore, with the introduction of capacitor commutated converters (CCC) by ABB in 1995 [17], the required short-circuit capacity of the AC system decreased. However, we begin to talk about a new era of HVDC from the operational demonstration of the first VSC HVDC system.

Currently, HVDC technology has been applied in several countries where it has been necessary to build new transmission lines to support the development energy sources located in remote areas such as offshore wind or hydro power.

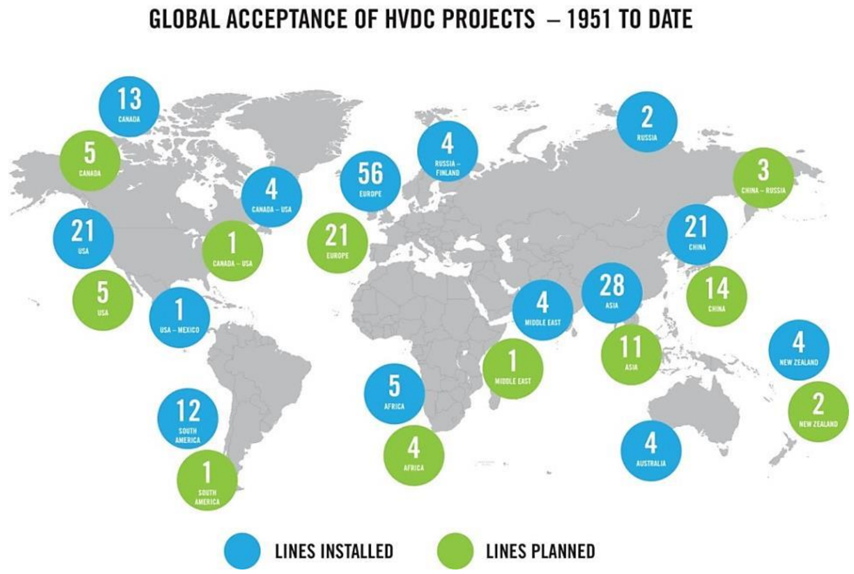


FIGURE 2: HVDC WORLD PROJECT MAP [40].

Nowadays, more than 179 HVDC transmission links are operating [19, 40]. Some of them located in United States, Scandinavia, Japan, Australia, Brazil, South Africa, India, and China and others more under construction as it is shown in Figure 2. HVDC technology has been a determining factor to improve the existing power systems or sometimes the only solution due to its features and advantages.

1.2. COMPARISON BETWEEN AC AND DC TRANSMISSION

There are important decisive factors at the moment to choose between an HVAC or HVDC transmission system like the economics of transmission, technical performance, reliability and environmental impact just to mention. These factors must be considered as part of an overall long term of the transmission planning, due to the continuous development of the electric grids by increasing power demand.

1.2.1. TECHNICAL ASPECTS

One of the most important factors is the technical feasibility to implement a link with each one of the technologies. The following are some positive features in the technical performance of DC transmission over AC:

- Figure 3 shows how the power of the HVDC transmission system remains constant regardless the distance, while in HVAC the transmission capacity decrease with the length of the lines, due to inductive effects.

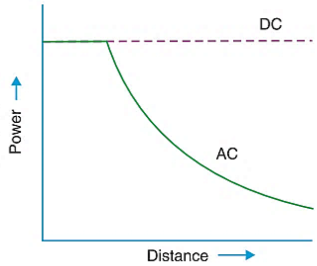


FIGURE 3: RELATIONSHIP BETWEEN POWER TRANSMITTED CAPACITY AND DISTANCE OF AC AND DC LINES [8].

  AC lines have a limitation of length due to its inductive effects. These effects produce an angle difference between the sending and receiving end of the line, therefore for the purpose of the active power transmission, the line requires the consumption of reactive power which can lead to the instability of the system, in some cases is necessary the use of methods of reactive power compensation. This consumption increases with the length up to point where the line only transmits reactive power and no active power. However, inductive effects do not constrain the transmission capacity of the HVDC overhead line or cable, and this means that all transmitted power is active power taking advantage of more transmission capacity and high stability. Consequently, there is not a limitation of the maximum length of the line.

- For long cable links, HVDC will in most cases offer the only viable technical transmission alternative because for AC cable the high charging current will limit the maximum possible transmission distance [8]. With HVDC there is no such limitation, and this is a particular advantage for transmission across open sea or into large cities.

- DC technology is asynchronous, i.e. that it can be adjusted to any voltage and frequency it receives [42]. This feature allows HVDC interconnections between two AC systems with different voltage and frequency, which cannot be synchronized.

- HVDC has an accurate and fast control of the active power in the link. In several cases, an HVDC connection can also improve the operation of AC power systems through additional control facilities. Among of these control functions are constant frequency control, redistribution of the power flow in the AC network, damping of power swings in the AC networks, etc. [62]. In many cases, these extra functions can make feasible the reliable increase of power transmission capacity in AC transmission lines.

- The losses in the system are another point to consider, those produced in the lines, converters and transformers. In DC lines, lower losses occur than in the AC in relation to its length. Therefore, there will be a certain distance in which they are equal and from that distance HVDC systems will have lower losses than HVAC as it is shown in Figure 4 as an example. This distance will depend on the installed power and cable types used in each case.

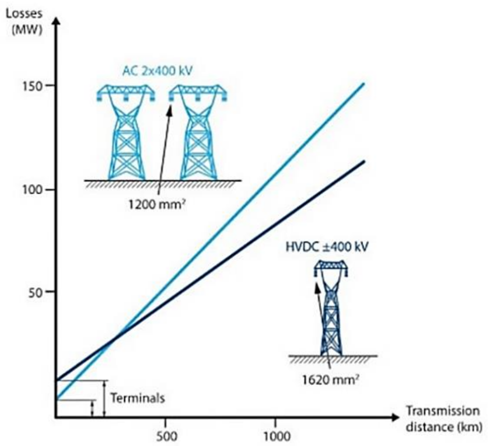


FIGURE 4: LOSSES IN 1,200MW OVERHEAD LINE AC VS. DC [41].

1.2.2. Economic Aspects

When is possible to implement a transmission system either HVAC or HVDC, it is necessary to consider other additional factors. Usually, the most important could be the economical aspect. Then to begin with the analysis of the total cost of a transmission system, it will be indispensable to have both the direct cost of the project (i.e. lines and converters/transformers) and the indirect costs.

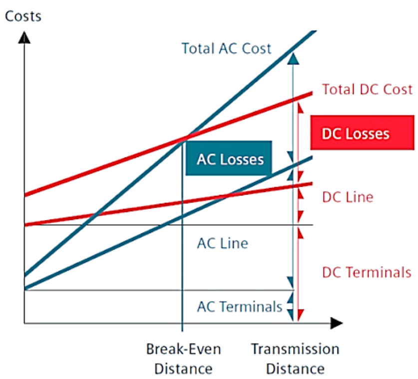


FIGURE 5: COST COMPARISON BETWEEN THE AC AND DC TRANSMISSION SYSTEMS ACCORDING TO THE LENGTH OF THE TRANSMISSION LINE [62].

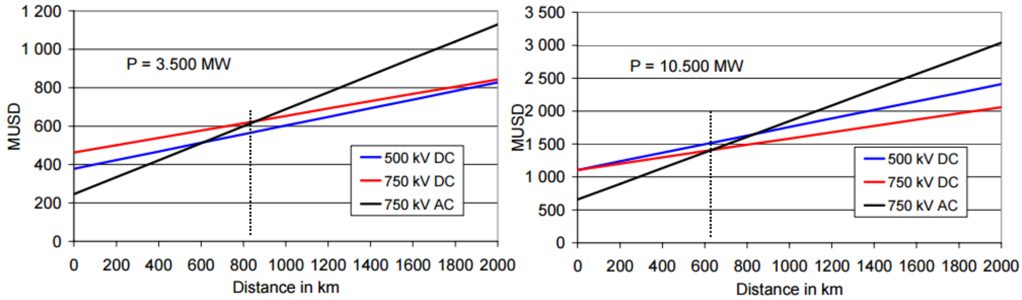


FIGURE 6: TOTAL COST FOR STATIONS AND TRANSMISSION LINES FOR 3,500 MW AND 10,000MW [63].

Figure 5 shows a typical cost comparison curve between AC and DC considering: AC vs. DC station terminal costs, AC and DC line costs, and AC vs DC capitalized value of losses. Figure 6 shows the comparison of total cost/distance in two overhead line transmission systems of 3,500MW and 10,000 MW.

Comparing both figures, it is observed how for each system, the break-even distance decreases for greater power and voltage capacities. This is due to the higher fixed costs of HVDC systems, that are adjusted by the lower cost of the HVDC lines (i.e. less number of lines), the support structure (i.e. less mechanical strength to support) and losses (i.e. greater losses in the converter station are compensated by lower losses in the HVDC lines).

The break-even distance is approximately between 500 and 800 km for OHL and is about 50 km for subsea cables [8, 41]. This distance depends on different factors and analysis must be prepared for each particular case when is consider in choosing an AC or HVDC transmission system.

1.2.3. Environmental Aspects

The effect of high voltage on the environment and human being is an interesting and even controversial issue in recent years. According to [18, 24, 62], the possible impacts on the environment of high voltage transmission systems are: effects of magnetic fields, effects of electric fields, RF interference, audible noise, visual impacts, ground currents, corrosion effects, the use of land for transmission line and substation facilities that was previously used for other purposes.

The HVDC transmission systems have specific features concerned to all above environmental impacts that must be considered when choosing transmission lines routes and in the development of a transmission line project. For this reason, each of these ecological aspects is presented respect to the features of DC and AC systems as follows:

- The magnetic field describes the magnetic influence of electric currents and magnetic materials. The magnetic field around the transmission lines is similar to the natural magnetic field produced by the Earth; consequently, it cannot affect negatively. The limit on the magnetic field strength of an AC power transmission system varies from 10 to 50 μT [63]. While the magnetic fields associated with DC lines produce no perceivable effects, for example for ± 450 kV DC transmission line the flux density is about 25 μT, where the Earth's natural magnetic field is 40 μT [24].

- In monopolar configurations with a ground return path, the magnetic field can modify the readings of a compass near to the lines; this problem can be solved using a metallic return path to cancel such magnetic field. Also, a ground return path can induce a current in pipelines or metallic conductors nearby the converter stations; which can produce corrosion effects in those elements [24].

- The electric field is produced by the combination of the electrostatic field created by the OHL voltage and the space charge field produced by the line's corona. The electric field may change with the weather, seasonal variation and relative humidity [24]. Usually, the human being feels some discomfort under AC transmission lines that is not perceived under DC lines according to researches related with the environmental influence of electric fields around HVDC transmission lines made in Canada and Russia [18]. This discomfort involves spark discharges from persons to scrubs, grass and other vegetation.

  The discharges can occur under the effect of the HVDC line electric fields; however, are uncommon in contrast to the discharges produced by AC transmission line fields which can be 100 discharges per second at 50 Hz [18]. Moreover, there are recommendations to reduce the ecological effect of electrical fields from transmission lines such as mandatory limits on the total electric field of a DC line by a certain level of space charge; and limits independently on the electrostatic field and ion current density [18]. Also, regulations are created to guarantee the welfare of people working in DC electric fields.

- Regarding overhead lines, the size of the support structures for an HVDC system with the same level of power transmission is lower than an AC. This feature of HVDC systems causes a decrease in the size of the corridor and right of way; reduces the visual impacts; saves lands compensation for new projects and makes possible the increase of the power transmission capacity for existing right of way [62]. In Figure 7, there is a comparison between DC and AC overhead transmission line, and it is shown the land coverage and the associated right-of-way for each of them.

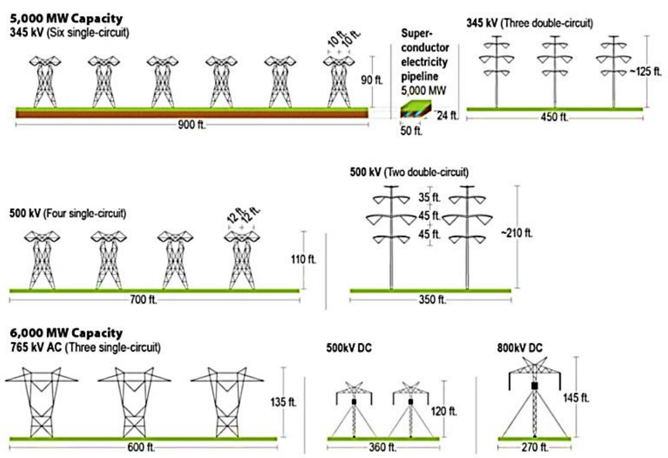


FIGURE 7: COMPARISON OF RIGHT OF WAY REQUIREMENTS FOR VARIOUS TRANSMISSION SYSTEMS [43].

- The radio frequency interference is caused by the corona discharge around conductors of the power transmission lines. While on an HVDC line the RF interference is generated only by positive pole conductors, for an HVAC is generated by the three phases.

  Just to compare, supposing equal capacity conductors and maximum levels of electrical field intensity on the conductors' surfaces, the RI level of HVDC lines is typically lower by 6-8 dB than of HVAC lines [18]. To solve this interference, it is necessary to install appropriate filters in the HVDC lines.

- The audible noise is another important factor to consider; which both AC and DC transmission systems produce it and is very common with the fair weather. However, when there is bad weather, the noise levels from a DC system will reduce, not like the noise levels from AC lines. Therefore, there are regulations such as the audible noise from transmission lines should not exceed, in residential areas, 50 dB during the day, or 40 dB at night [18]. In general, the methods applied to control the noise for a DC transmission line are the same for AC.

1.3. HVDC Transmission Applications

There are different areas of application of HVDC technology, and although there are several reasons for selection such as [23]: economic feasibility, connect asynchronous networks, reduce fault currents, use long underground or submarine wire circuits, avoid network congestion, share utility rights of way without degradation of reliability, and to relieve environmental impact.

HVDC transmission applications include the following categories and any arrangement frequently involves a combination of two or more of these [23, 61]:

- Long-distance bulk power delivery from remote resources such as hydropower, mine-mouth power plants, or large scale wind farms, where AC transmission would be inefficient, unfeasible or subject to environmental restrictions.
- Links through underground or submarine cables due to the fact that there is not constraint to limit the distance or power level for HVDC, and even better, there are significant savings in costs of installed cable and losses when using HVDC transmission.
- Asynchronous systems ties for economic reasons or simply to make more reliable the operation of the system. These asynchronous HVDC links act as an effective firewall against propagation of cascading outages in one network to another network from passing.
- Power delivery to large urban areas, where the construction of new transmission systems is difficult because of the right of way and land use restrictions.
- Supply isolated loads on islands or transmit production of offshore platforms over long-distance thanks to the self-commutation, dynamic voltage control, and black-start capability of HVDC technologies.
- The addition of power infeed without significantly increasing the short circuit level of the receiving AC system.
- Improve of AC system performance by the accurate control of HVDC.

1.4. HVDC TECHNOLOGY

Figure 8 shows a basic scheme of an HVDC link. In the operation of HVDC systems, the electrical current is converted from AC to DC using a rectifier at the sending end. The DC power is independent of the AC supply frequency and phase. Then, the DC power is transmitted through a conduction medium that can be an OHL, a cable or a short length of busbar; to the receiving end, where an inverter is responsible for the conversion of DC to AC.

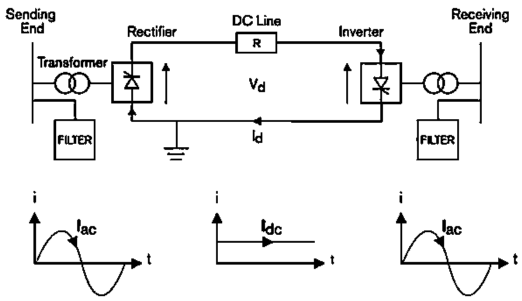


FIGURE 8: BASIC HVDC TRANSMISSION [61].

There are two basic converter technologies used in modern HVDC transmission systems: the line-commutated converters and the self-commutated converters, which main features are presented in Table 1.

TABLE 1: COMPARISON BETWEEN LCC AND VSC TECHNOLOGY BASED ON [26, 64].

Line-Commutated Converters	Self-Commutated Converters
• Current Sourced Converter (CSC) • Based on thyristor technology. • Semiconductors which can tolerate voltage in any polarity. • The current direction does not change • The output voltage can be any polarity to change the power direction. • Inductively storing energy	• Voltage Sourced Converter (VSC) • Based on transistor (IGBT, GTO, etc.) technology. • Semiconductors which can permit current in both directions. • The polarity of output voltage does not change. • Changes in the current direction change the power direction. • Capacitive energy store

Previously, there has been presented the most important criteria when deciding between an HVDC or HVAC system. If eventually it is decided to use the HVDC technology, some factors to consider in determining the type of technology that will be implemented in the system are [26, 44, 64]:

- The modularity of a VSC technology makes it easier and faster to implement since most of the equipment is mounted at the factory.
- The VSC technology always needs to install two cables due to its bipolar nature, while LCC allows monopolar configurations.
- VSC technology allows independent frequency and voltage control of the AC network. The short-circuit current and the presence of reactive power are not as decisive factors for the correct operation of a system with VSC technology as they are for an LCC. LCC technology, on the other hand, needs reactive power to operate, which makes the presence of voltage on both sides of a link essential for the stations to work. For this reason, VSC technology can feed passive networks, for example, small islands, oil rigs, etc. In contrast, LCC needs active networks at both ends and for use in passive networks will require the installation of synchronous compensators.
- The VSC technology allows independent and almost total control of active and reactive power. The LCC only allows controlling the active power, while the reactive power is a function of the transmitted active.

- LCC conversion stations require large filters due to the high reactive power consumption of the converters. The VSC requires smaller filters without the need for converter compensation.
- LCC technology needs communication between the two conversion stations on both sides of the link. This is not necessary in the case of implementing VSC.
- In the event of a power disruption, VSC systems can apply a black-start in any situation while for LCCs additional equipment is required.
- In the case of voltage collapse or blackout, the VSC can immediately switch to its internal voltage and frequency reference and disconnect from the network. Then, the inverter can function as an idle static generator, prepared to be connected to a black network to provide the first electricity to the main loads; as long as the converter on the other end of the DC link is not affected by the blackout.
- Although both technologies allow reversal of the direction of power transfer, with VSC is possible without the change of polarity. This affects the insulation of the conductors in VSC cables, which can become of smaller thickness.
- VSC HVDC can significant reduce line ohmic losses and magnetization losses in the connected networks.

1.5. COMPONENTS OF HVDC SYSTEMS

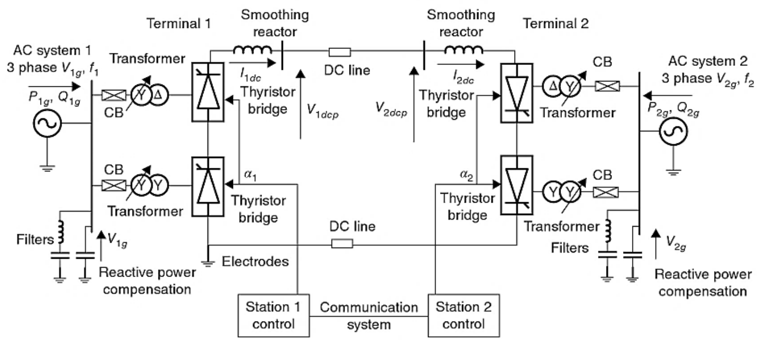


FIGURE 9: MAIN COMPONENTS OF AN HVDC TRANSMISSION SYSTEM [7].

Although many of the currently installed consumptions run on direct current, they are all designed to perform the conversion from the level of alternating current to which they are connected to the continuous needed for their operation. In the same way, is with the generation of electric energy that is produced in the alternative current.

This means that to carry out the energy transport using HVDC, it is necessary to convert it from AC to DC for later, to perform the reverse transformation from DC to AC. Therefore, the main elements involved in this process are shown in Figure 9 and detailed below.

1.5.1. CONVERTER STATION

The major component of an HVDC transmission system is the converter station where conversion from AC to DC (rectifier station) and from DC to AC (inverter station) is performed. The various components of a converter station are presented below:

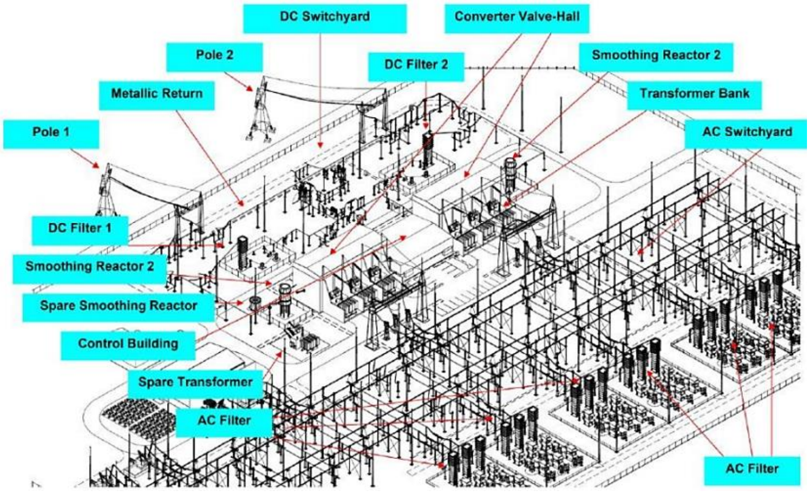


FIGURE 10: MAIN COMPONENTS OF A CONVERTER STATION [15].

1.5.1.1. AC SWITCHYARD

The AC system connects to an HVDC converter station through the AC bus bar known as converter bus also. Among the connections and devices located in this bar are: the AC connections, AC harmonic filters, HF filters components, surge arresters, AC circuit breakers, disconnectors, earth switches and other possible loads such as auxiliary supply transformer, reactive power equipment, etc.

In an HVDC converter station two cases can be present, and in any of them, the space occupied for the AC switchyard is according to the AC voltage level:

- The converter station is part of a major node on the network, and consequently, there could be many feeders, each with its associated towers, line end reactors, step-up/down transformers, etc.
- The converter station is located on the edge of the network, and as a result, there could be only fewer feeders with the converter equipment.

1.5.1.2. CONVERTER UNIT

The converters, as mentioned above, aim to transform alternating and continuous current on both sides of the transmission lines. In the process of converting AC to DC, it is desired to achieve an input with the greatest number of possible phases, since this allows delivering a near flat continuous signal (minimum ripple) to the output before connecting a filter. These converters can apply the LCC; VSC or IGTCT technology.

1.5.1.3. CONVERTER TRANSFORMER

The function of the transformers is to convert the AC voltage of the input lines to the AC input voltage of the HVAC / HVDC converters. Therefore, they act as an interface between the AC system and the HVDC converter, while performing essential functions such as [61, 62]:

- Provide the necessary insulation between the AC network and the converter.
- Offer the correct voltage to converters.
- Limit the effects of steady state AC voltage change during operation conditions (tap-changers).
- Provide fault-limiting impedance.
- Provide the 30° or 150° phase shift needed for twelve-pulse converters operation by star and delta windings.

The converter transformer is the largest element to be sent to the site in an HVDC project. Therefore, transport restrictions for instance: weight or height, have a significant impact on the selected converter transformer arrangement. Figure 11 illustrates the standard transformer arrangements in HVDC schemes.

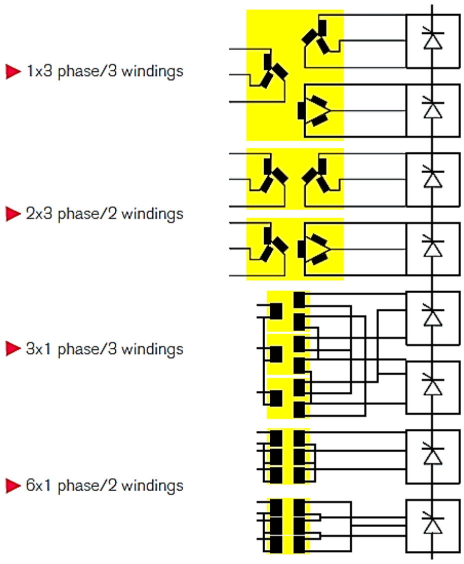


FIGURE 11: TYPICAL CONVERTER TRANSFORMER ARRANGEMENTS [61].

In order to obtain the lowest possible costs, the number of elements in which the converter transformer must be decomposed must be minimized; as a result, a 3-phase/3-winding transformer usually has the lowest cost. But, considering transport restrictions, this scheme may not be functional, which leads to the consideration of another arrangement. On the other hand, when considering a spare transformer to ensure the availability of the scheme, it is more cost-effective for example to use a 1-phase/3-winding transformer because one spare unit can replace any of the in-service units [61].

Finally, because the converter transformers are subject to particular conditions [61] such as a combination of voltage stresses, a high harmonic content of the operating current and DC premagnetization of the core; they must be designed according to the individual requirements of HVDC systems.

1.5.1.4. HARMONIC FILTERS

Due to the high harmonic content generated in the converter, it is necessary to install filters on both AC and DC side. Limit values are depending on the class of interference to be attenuated. Some of these values are [65]:

- At frequencies between 150 kHz and 500 kHz shall be generated noise below -30dBm (0dBm = 0.775V, 1μW about 600Ω and a bandwidth of 4 kHz).
- In the radio frequency range of 500 kHz to 30 MHz, the ENV50121-5 standard must be met.
- Corona noise close to the conversion station and overhead lines should not exceed 100μV/m between 500 kHz and 30 MHz

AC FILTERS

Filters on the AC side of the conversion station are responsible for absorbing the harmonics generated by the converter and for providing a part of the reactive power required by the converter which depends on the active power, the transformer reactance and the control angle of the valves. The order of the harmonics depends on the type of converter. These filters can be first, second or third order with resonance frequencies between 3 and 24 Hz. These passive filters can be complemented by electronically controlled active filters, which reach up to eliminate harmonics of order 50 if necessary. These filters must meet a number of requirements [65]:

Individual harmonic distortion $$D_h = \frac{U_h}{U_1} \leq 1\,\% \qquad (1)$$

Total harmonic distortion $$THD = \sqrt{\sum_{h=2}^{50} \left(\frac{U_h}{U_1} \right)^2} \leq 2\ \% \qquad (2)$$

Telephone influence factor $$TIF = \sqrt{\sum_{h=2}^{50} \left(\frac{U_h TIF_h}{U_1} \right)^2} \leq 40 \qquad (3)$$

Where:

U_h: is the h:th harmonic (phase to ground) voltage.

U1: is the nominal fundamental frequency (phase to ground) voltage.

TIF_h: is the weighting factor for the h:th harmonic according to EEI Publication 60-68 (1960).

Usually, the AC harmonic filters are composed of a high voltage connected capacitor bank in series with a medium voltage circuit comprising air-cored air-insulated reactors, resistors and capacitor banks. These components are chosen to provide the required performance from the AC harmonic filter and to ensure that the filter is suitably rated [61].

DC FILTERS

These filters are installed on the DC side to reduce the AC component of the continuous signal to be obtained (ripple reduction). There are several types of filter design where single and multiple-tuned filters with or without the high-pass feature are common. Also, one or several types of DC filter can be utilized in a converter station [62].

During the design of these filters must consider interference on nearby telephone lines. This defect is quantified by the following expression [65]:

$$I_{eq} = (1/P_{800}) * \sqrt{\sum_f (P_f * I_f)^2} \qquad (4)$$

Where:

I_{eq}: is the psophometrically weighted, 800 Hz equivalent disturbing current.

I_f : is the vector sum of harmonic currents in cable pair conductors and screens at frequency.

f: is the frequency ≤ 2500 Hz.

P_f: is the psophometric weight at frequency f.

ACTIVE HARMONIC FILTERS

Active filters can be used as a complement to passive filters because of their superior performance. They could be connected on the DC side or on the AC side of the converter. The connection to the high voltage system is achieved through a passive filter, establishing a so-called hybrid filter. With this arrangement, the level of voltage and transient stresses in the active part are restricted, causing that the equipment to be used are of lower ratings [62].

HIGH FREQUENCY (HF/PLC) FILTERS

The conversion process can produce high-frequency interference, which can be propagated to the AC system from the converter bus. Although, the magnitude and frequency of this interference are often not of vital importance for the safe operation of the AC system, there are occasions where this high-frequency interference may be disadvantageous, for example when the AC system employs Power Line Carrier Communication (PLCC).

The PLC communication is a method that transmits a communication signal superimposed on the fundamental frequency of the voltage signal of an AC power system. The primary goals of this system application are the protection of the transmission line, communication between operating personnel in the stations and carrying of telemetering [66]. Therefore, sometimes is indispensable to integrate a High Frequency (HF) filter (or PLC filter) in the connection between the bus and the converter with the purpose of regulating the high-frequency interference because it can overlap with the frequencies used for PLC communications.

In the same way, as with the AC harmonic filter, the HF filter involves a high voltage connected capacitor bank, an air-core air-insulated reactor and an additional low voltage circuit composed of capacitors, reactors, and resistors which are denoted to as a tuning pack [61].

1.5.1.5. Reactive Power Source

The reactive power is supplied from the AC filters, shunt banks, or series capacitors that are an integral part of the converter station [23, 61]. The AC system must adjust any excess or deficit in reactive power from these local sources. The difference in reactive power needs to be kept within a certain range to maintain the AC voltage in the required tolerance.

It is important to highlight that the weaker the AC system or the further away the converter is from generation, the more efficient the reactive power exchange must be to remain within the required voltage tolerance.

1.5.1.6. Smoothing Reactor

The DC smoothing reactor is usually a large air-cored air-insulated reactor and has several functions within an HVDC scheme like the followings [61, 62]:

- Reduce ripple in direct current on transmission lines because it can cause high overvoltage in the transformer and the smoothing reactor.
- Reduce the maximum fault current that could flow from the DC transmission system to the converter fault.
- Modify DC side resonances at frequencies other than multiples of the fundamental AC. As this is very important to avoid the amplification effect for harmonics originally from the AC system, such as negative sequence and transformer saturation.
- Reduce harmonic currents.
- Protect thyristor valves from fast front transients originated in transmission lines such as a lightning strike.
- For schemes rated at or lower than 500 kV, is mostly located at the high voltage terminal of the HVDC converter; while over 500 kV, the DC smoothing reactor is usually split between the high voltage and neutral terminals.

1.5.1.7. Surge Arrester

The primary task of an arrester is to protect the equipment from the effects of overvoltage. Additionally, the arrester must be able to resist typical surges without incurring any damage. It is characterized by offering a high resistance under normal operating conditions, low resistance in case of contingency and sufficient energy absorption capability for a stable operation. These protections are installed between the different stages of the transmission system and conversion [62].

The arrester is used to ground the different areas of the installation in case of lightning or over-currents, but also take into account the voltage differences between components that may appear in case of connecting different arrester to a different ground or the possibility of reflected currents on the network [62].

1.5.2. DC TRANSMISSION CIRCUIT

1.5.2.1. DC TRANSMISSION LINE

The OHL that are used in HVDC transmission have some advantages over HVAC. The towers are mechanically designed as if an AC line is involved; however, it should be noted differences in the configuration of the conductors, the electric field and the design of the insulators.

TOWERS

HVDC towers will be more moderate and simple since they hold fewer conductors the towers in an HVAC system. This fact impacts on their size, reducing them, and therefore, this causes lower costs of civil works and materials for their installation. As mentioned before, its design it is similar to AC systems.

INSULATION

The types of insulators commonly applied to transmission lines today are cap and pin; long-rod porcelain; and composite long-rod. The insulators design has a significant impact not only on the correct operation of the system without disturbances but also on the life of the project. Some of the conditions to take into account in the design of the insulators are [62]:

- The general layout of insulation is established by the IEC 60815.
- This IEC is a standard for AC lines; therefore some adjustments must be made to the design.
- Insulators under DC voltage operation must bear more unfavorable conditions than under AC due to higher collection of surface contamination caused. So, a DC pollution factor as per recommendation of CIGRE has to be applied.

1.5.2.2. DC CABLE

There are different technologies available in cables for underground or submarine DC. Some of them common to existing ones in AC, some of these technologies [62]:

- Mass-Impregnated Cable: It consists of a central conductor covered by copper lamination layers of paper impregnated with oil and resins. Then, the cable is covered with layers of extruded polyethene and galvanized steel which protects against corrosion and mechanical deformations during operation. Also, it is usually reinforced with a layer of steel and/or lead. Its capacity is limited by the temperature that can reach the conductor but is not limited in length.
- Oil-Filled Cable: This cable is similar to Impregnated Mass, but uses a lower density impregnated paper and a longitudinal duct in the conductor shaft for cooling oil. This conductor also reaches great depths, but its length is limited due to the need to circulate the liquid refrigerant along the cable, for which pumping

stations are necessary. Also, the risk of leakage makes it environmentally challenged.

- XLPE Cable (Cross – Linked Polythene): This cable uses as an insulator an extruded polymer, resulting in a cable with dry insulation. This material allows a working temperature of 90°C and a short-circuit temperature up to 250°C.
- PPLP Cable (Polypropylene Laminated Paper): Uses insulation layers formed by laminating paper and propylene to reduce the dielectric losses. It is employed in HVDC due to its thermal behavior and its insulation, superior to those of impregnated paper, which results in a greater capacity of transport.
- Extruded for VSC: This technology appears with the aim of overcoming the limitations of existing extruded cables in conventional HVDC. These new plastic cables combine high capacity to work at high DC voltages with low weight and high powers.

1.5.2.3. EARTH ELECTRODE

The earth electrode is of particular importance in the case of monopolar systems since it performs the functions of return of the current. In bipolar systems, it performs similar functions to the neutral in a three-phase system, in the case of a balanced system does not perform any function, but in the usual case of asymmetries leads to ground the difference between both poles [61, 62].

The earth electrodes are usually connected at some distance from the conversion station to avoid interference with equipment installed in the station by earth currents. Depending on the needs, it can be installed horizontally or vertically on land, in coastal areas or deeper, may be anode and cathode, making the function of electrodes in underwater connections.

1.5.2.4. DC SWITCHYARD

The switchyard on the DC side of the converter, usually, includes disconnectors and earth switches for the scheme reconfiguration and the secure maintenance operation. The switches allow the conversion station to operate in its different possible modes to keep the system in operation. They are produced in an SF6 atmosphere and are connected in parallel with filters to absorb transient charge created in the opening and closing of the switches. The following switches can be identified from an HVDC scheme according to the function performed [61, 62]:

- High-Speed Neutral Bus Ground Switch (HSNBGS): is essential to connect the station neutral to the station ground grid if the ground electrode path becomes isolated.
- High-Speed Neutral Bus Switch (HSNBS): Its main duty is to commutate some direct current into the ground electrode path in case of faults to ground at the station neutral.
- Metallic Return Transfer Breaker (MRTB): is necessary for the shift from ground to metallic return without interruption of power flow.
- Ground Return Transfer Switch (GRTS): is used for the retransfer from metallic return to bipolar operation via ground return, also without interruption of power flow.

1.6. HVDC CONFIGURATIONS

HVDC technology allows the implementation of one or another system configuration in function of the objective. The main features of both the connection types and the configurations of HVDC systems will briefly be explained below:

1.6.1. CONNECTION TYPES

1.6.1.1. HOMOPOLAR

The homopolar link (Figure 12) has two conductors with the same polarity, and a metallic return conductor is used, which will flow double the nominal current in one of the lines. In this configuration, poles are operated in parallel that decreases the cost of insulation.

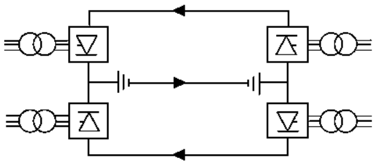


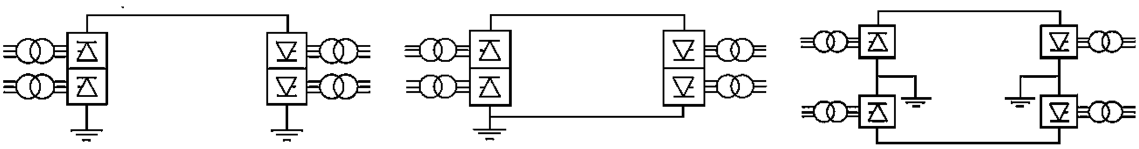
FIGURE 12: HOMOPOLAR LINK [8].

1.6.1.2. MONOPOLAR

The monopolar connections use only one conductor to transmit the electrical energy, as it is shown in Figure 13. The return is made by electrodes connected to the conversion stations, which act as cathode and anode.

This type of connection is used when the systems to be connected are separated by huge distances and where the installation of the return cable can be a considerable saving. It is also used in submarine systems, where the sea performs the return functions, offering fewer losses than a metallic return, or when it is not possible to use one of the phases of a bipolar connection.

Some systems include a monopolar metallic return when it is not possible to do through electrodes connected to ground (usually due to environmental issues) or when losses are too important.



Monopole with ground return path

Monopole with metallic return path

Monopole with midpoint grounded

FIGURE 13: MONOPOLAR SYSTEMS [23].

1.6.1.3. BIPOLAR

Bipolar connections are usually used when the capacity of a monopolar link is exceeded. Also, it provides greater reliability to the system, since it can be used as a monopolar in case one of the poles is out of service and can transmit, depending on the operating criteria, more than 50% of the actual power [23].

The bipolar links can be connected to ground by electrodes or connected to each other by a metallic return path, as shown in Figure 14. Whatever the system, this electrode only carries the difference between the two poles; its function is similar to the neutral of a three-phase system.

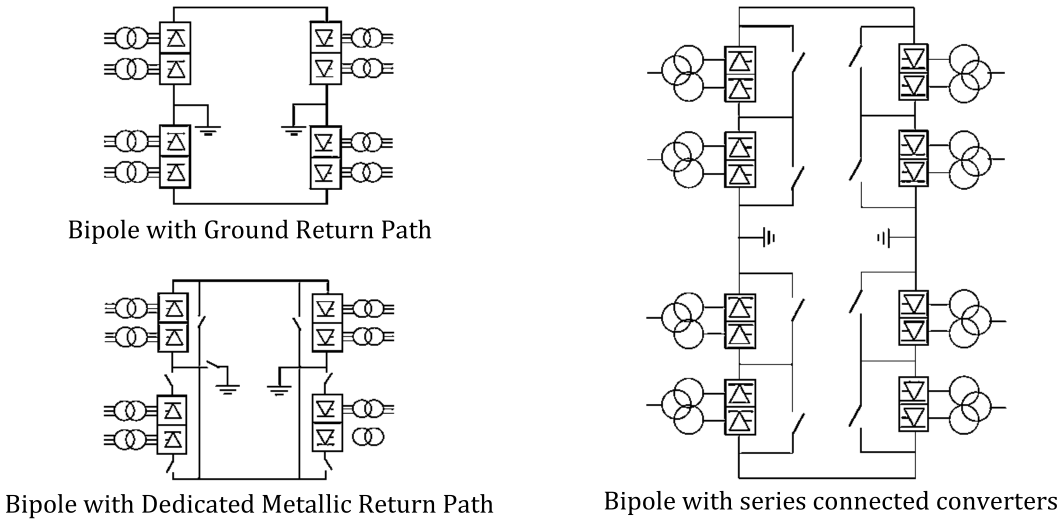


FIGURE 14: BIPOLAR SYSTEMS [23].

1.6.2. SYSTEM CONFIGURATIONS

1.6.2.1. BACK TO BACK

The back to back configuration is used to connect two asynchronous or different frequency systems very close since the connection is made inside the substation. This configuration does not need a transmission line between rectifiers and inverters since they are located in the same establishment. The connections can be monopolar or bipolar.

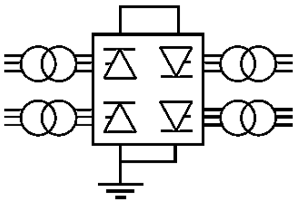


FIGURE 15: BACK TO BACK SYSTEM [23].

1.6.2.2. POINT TO POINT

Point-to-point configuration is the most common configuration in HVDC. It is used to connect two substations when the HVDC connection is more profitable than the HVAC or when the HVDC solution is the only technically feasible solution. In this case, one of the stations will operate as a rectifier and the other as an inverter depending on the needs of the system.

The point to point configuration is also used in submarine connections, allowing the transmission to isolated loads or isolated generation systems, or to support island systems from continental systems, among other applications.

1.6.2.3. MULTITERMINAL

Multiterminal configuration occurs when three or more substations are connected to an HVDC system. This connection can be:

- Parallel: All substations are connected to the same voltage. It is used when all substations exceed 10% of the total power of the rectifier stations [23].
- Series: The substations are connected in series, and each has a different voltage. A substation connected in series cannot consume more than 10% of

the total power of the rectifier stations so as not to affect the level of voltage that reaches the others [23].

- Mixed: It is a combination of the systems mentioned above.

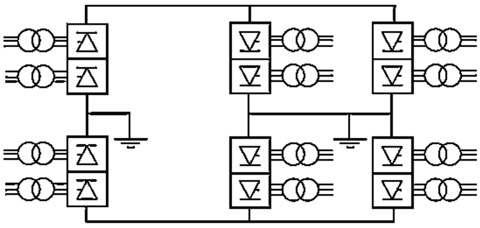


FIGURE 16: MULTITERMINAL SYSTEM [23].

1.7. HVDC CONTROL, PROTECTION AND OPERATING PRINCIPLES

The main objectives for the implementation of a control system in an HVDC transmission system are linked to the guarantee of reliable and safe transmission of energy. This control system must operate with great efficiency and respond to changes in demand that may arise, to maintain the stability of the system.

The tasks of a modern operation and monitoring system within the HVDC control system include the following [23, 62]:

- Status information of the system.
- Operator guidance to ensure proper operation and explain conditions.
- Monitoring of the whole installation and auxiliary equipment.
- A visual display, providing an overview of the entire system.
- Troubleshooting support with clear messages to quickly resume operation.
- Display and sorting of time tagged events.
- Display and archiving of messages.
- Automatic generation of process reports.
- Analysis of operating mode based on user defined and archived data.
- Generation of process data reports.

All control and protection systems that contribute to the energy availability must be configured redundantly because this covers any single faults in the control and protection equipment without loss of power. Moreover, the design process of any control system must have many defined review steps to allow verification of the control and protection system functionality and performance before delivery to the site.

1.7.1. CONTROL AND PROTECTION LEVEL

1.7.1.1. POWER CONTROL

The most important control in a DC system is the active power control. The standard control of this type of installations is the control using set-point of power or current [23].

In a system with LCC technology, the reactive power depends exclusively on the active power signal. For the control of active power in LCC HVDC, one terminal sets the DC voltage level whereas the other terminal adjusts its current by controlling its output voltage relative to that maintained by the voltage setting terminal. Since the DC line resistance is low, big changes in current and therefore power can be made with quite small changes in firing angle (alpha) [23]. There are two methods for controlling the converter DC output voltage [23]:

- Modify the ratio between the DC voltage and the AC voltage by changing the delay angle.
- Change the converter AC voltage through load tap changers on the converter transformer.

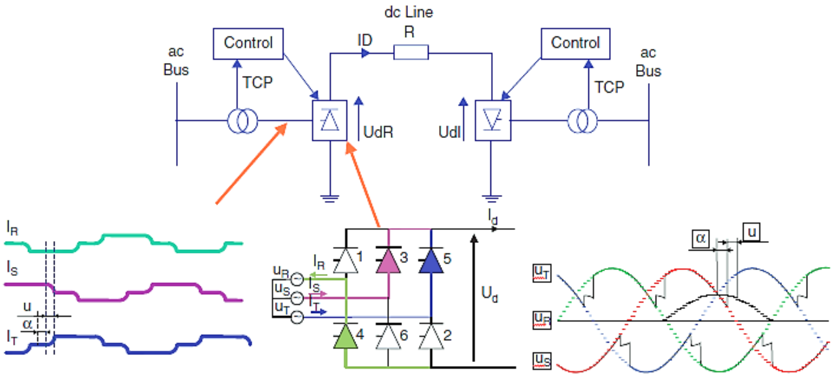


FIGURE 17: PRINCIPLE CONTROL OF LCC HVDC TRANSMISSION [23].

In Figure 17 is shown the typical transformer current and DC bridge voltage waveforms along with the controlled items U_d, I_d, and tap changer position (TCP).

In a system with VSC technology, the active and reactive power controls are completely independent. The system is designed for a range of active and reactive power. Within that range, the system can have any point of operation. For VSC HVDC, the active power can be controlled by changing the phase angle of the converter AC voltage concerning the filter bus voltage, while the reactive power can be controlled by adjusting the magnitude of the fundamental component of the converter AC voltage concerning the filter bus voltage [23].

Figure 18 presents the typical AC voltage waveforms before and after the ac filters along with the controlled items U_d, I_d, Q, and U_{ac}.

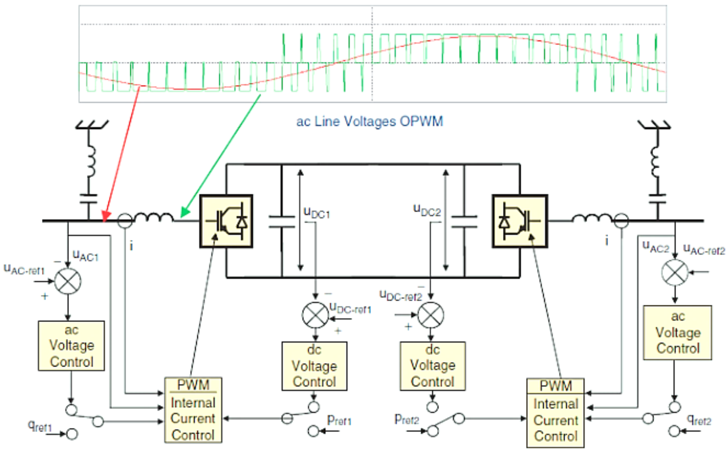


FIGURE 18: PRINCIPLE CONTROL OF VSC HVDC TRANSMISSION[23].

As well, there are secondary or emergency controls [61, 62] for instance:

- Frequency control. Depending on the frequency of the system, the HVDC system will respond by changing the active power set point.
- Emergency Controls: Run-ups, Run-backs.
- Damping of sub-synchronous resonances.

- Damping of power oscillations.
- Fast Power Inversion (LCC).
- Black Start (VSC).

1.7.1.2. PROTECTION

The protection system has the task of protecting the equipment or preventing damages to the different components, either due to faults or overstresses. The protection system can be divided into two main areas, i.e. DC and AC protection, which in turn, can be divided into different protection zones. DC protection includes converter protection, DC busbar protection, DC filter protection, electrode protection and line protection. While AC protection includes AC busbar protection, AC line protection, AC network transformer protection, AC filter protection and conversion transformer protection [62].

Usually, each protection zone is covered by two separate protection units, i.e. the primary protection unit and the secondary protection unit or back-up. The protection functions of the different relay units must be efficiently executed for any operating condition to ensure that all possible faults will be detected, announced, and cleared.

2. STATUS AND FUTURE OUTLOOK OF GERMAN TRANSMISSION NETWORK

Germany has experienced large growth in the use of renewables after it made the decision in 2011 to leave out nuclear power for 2022, which had played a major role in generating electricity in the country [45]. Due to the nuclear phase-out policies and favorable tariffs approved for renewable energies; these have experienced a remarkable growth in the renewable shares of electricity production in Germany, which increased from 8.8% in 2002 to 33.4% in 2016 [46].

However, this transition of energy, known as Energiewende presents the greatest challenges to the high voltage transmission network, due to; for example, electricity produced from wind turbine farms often exceeds grid capacity. This also happens with electricity generated from solar energy [47, 67].

On the one hand, the proportion of electricity generated by renewable energies is expected to increase in the future. On the contrary, the power generation plants have traditionally been located close to the demand centers, but the expansion of renewables required a radical restructuring in this way. Most wind farms are located in the north of the Germany, while most solar farms are located to the south, with most of the electricity production centers located in remote and rural areas.

This has led to that in the coming years; one of the main objectives of the transmission system operators will be to develop the expansion of the German transmission network in a complete way since it must be able to meet the future requirements efficiently and environmentally friendly. Due to many of the existing lines are not designed to handle the current demands plus the growth that is expected with renewable sources. Many of these lines are reaching their limits [52] and a plan for the restructuring of the network is necessary. In this context, the German government has set the rules for transmission network operators to expand their networks quickly, coordinated and transparent. The steps for this system are given in [52, 53].

Not only, have the transmission networks needed to be made suitable for the energy transition, but also distribution networks. In the past, the distribution grids principal task was to "distribute" electricity to all households and companies. This has changed as renewables have expanded. Nowadays, they also provide the grid connections for the many wind and solar installations. This means that the lines now need to transport electricity in both directions as well as they need to balance the intermittent feed-in of renewables and the fluctuating electricity consumption of the companies and homes [52]. Therefore, the distribution grids not only need to be expanded and modernized, because in many cases they will also need to become smart grids.

2.1. TRANSMISSION NETWORK OPERATORS

The transmission network in Germany is divided into three voltage levels. Two of these three are classified as very high voltage at 220 kV and 380 kV, while the third level is classified as high voltage at 110 kV. This grid is connected to the European network, is managed and operated by four independent operators: Amprion, TenneT, TransnetBW and 50Hertz Transmission.

TABLE 2: FACTS AND FIGURES OF THE GERMAN TSOs BASED ON [48, 49, 50, 51].

	Amprion GmbH	**TransnetBW GmbH**	**TenneT TSO GmbH**	**50Hertz Transmission GmbH**
Location of headquarters	Dortmund, Germany	Stuttgart, Germany	Bayreuth, Germany	Berlin, Germany
Total Length of Power Lines	11,000 km	3,200 km	10,700 km	9,980 km
Network Area	73,100 km^2	34,600 km^2	140,000 km^2	109,360 km^2

2.2. GERMANY'S PLANS FOR ADDITIONAL TRANSMISSION INFRASTRUCTURE

As it was stated above, German energy policy has experienced great changes in recent years; and renewable energies will have an ever-increasing share of energy generation in the future. The Federal Government's energy strategy establishes a number of objectives, and the network expansion is and will continue to be of key importance in achieving these goals.

Some of the main projects applying HVDC technology and their characteristics are presented in Table 3, and in Annex A the locations of different planned projects are presented.

TABLE 3: HVDC PROJECTS IN GERMANY BASED ON [47, 55, 84].

Project	Capacity (MW)	Description	CAPEX 2015 (M€)	Country
ALEGrO	1,000	A 94 km HVDC underground link n between Belgium (Lixhe) and Germany (Oberzier), incl. internal reinforcements in the AC grid in Belgium	560 ± 35	Belgium / Germany
NordLink	1,400	A 514 km long subsea interconnector between southern Norway (Tonstad) and northern Germany (Wilster).	1,850	Norway / Germany
HVDC Line A North	2,000	A 380-kV OHL between Conneforde and Cloppenburg and a HVDC cable from Emden-East to Osterath	1,680 ± 200	Germany
HVDC Line A South	2,000	HVDC-link from the Region of Osterath (Rhineland) to the Region of Philippsburg (Baden-Württemberg). It's a pilot project with DC circuits on the same pylons as AC lines and will therefore deliver knowledge on combined AC/DC-corridors	1,070 ± 160	Germany
HVDC Line C	4 000	A HVDC connection from Northern Germany (areas of Brunsbüttel/Wilster) to Bavaria / Baden-Württemberg (areas of Großgartach/Grafenrheinfeld)	6,500 ± 1,300	Germany
HVDC Wolmirstedt to Isar (Line D)	2 000	HVDC-connection from North-East Germany (Wolmirstedt), to the South of Bavaria (Isar).	2,800 ±400	Germany

It is explained in [84] that the high costs reflect the priority of underground cables for DC-lines in Germany; as well the uncertainty range is high due to the early planning stage the exact realization is not clear because the majority of the projects are expected for medium to long term.

3. GENERAL CONSIDERATIONS FOR BASIC DESIGN

This section presents the basic parameters taken into consideration for the design of the HVDC link. The calculations and results obtained for the different proposed variants are presented and explained.

3.1. LOCATION OF THE LINE

To select the most convenient route some of the factors that should be considered are [12]:

- The cost of construction of the line.
- The cost of clearing the path where the line must pass.
- The cost of maintenance of the HVDC transmission line.
- Accessibility expenses of the line.
- Environmental considerations (Annex B).

Hence, for the analysis, two possible routes were considered:

ROUTE 1

The route 1 involved an HVDC bipolar point-to-point link between Röhrsdorf substation in Germany and Ernsthofen substation in Austria. The route that I proposed is shown in the Annex C (yellow line), and it followed the existing electrical corridors of transmission lines: Röhrsdorf-Hradec (445/446), Hradec-Chrást (430), Chrást-Přeštice (431), Přeštice-Kočín (432), Kočín-Dasný (473), and a new corridor between Dasný substation and Ernsthofen substation following highways.

The advantage of this route was the reduction of total distance of the link which implies the reduction of the number of towers required and length of conductors having an impact on the cost of line, but a disadvantage was the proposal of an entirely new electric corridor that could present complications due to environmental issues, as well the increase in the cost of clearing the path and construction.

ROUTE 2

The second route that I proposed is an HVDC bipolar point-to-point connection between Röhrsdorf substation in Germany and Dürnrohr substation in Austria. The route under analysis is shown in the Annex C (yellow line), and it followed the existing electrical corridors of transmission lines of Röhrsdorf-Hradec (445/446), Hradec-Chrást (430), Chrást-Přeštice (431), Přeštice-Kočín (432), Dasný-Slavětice (433), and Slavětice-Dürnrohr (434).

The advantage of this route was the possibility of using the existing corridors or part of them since the new line could run in parallel with the existing ones. But its disadvantage was to be slightly longer than route 1.

Finally, taking into consideration the factors mentioned above, I selected for this analysis the route 2 for the comparison of the different variants.

3.2. TRANSMISSION VOLTAGE

In order to select the transmission voltage, it must be considered that the chosen level has an impact on the cost and operation of the link. Due to this, it is desirable to use high voltages to reduce the size of the conductors which effects on the reduction of costs of the support structures; as well as to reduce line current for a given amount of power consequently reduces line losses.

I decided to design variants of a bipolar scheme with capacities of 1,500MW and 3,000MW, where each pole has to accommodate the half of the capacity during normal conditions. Consequently, to estimate the voltage to be implemented, I selected the standard voltage of ±400kV and ±500kV for the design to simplify the calculations. This was established on the basis of figures of Annex D suggested in [4, 69], which present the relations between power capacity, distance, and voltages.

Once the preliminary estimate of the link capacity was obtainable, an analysis of both technical and economic aspects was done to come up with the best choice among the variants.

TABLE 4: DIFFERENT VARIANTS FOR THE ANALYSIS.

Variant	Length (km)	Capacity (MW)	Voltage (kV)	Scheme	Converter Station	Observations
Variant A	530	1,500	±400	PTP Bipolar	LCC/VSC	Adjacent - New Tower
Variant B	530	3,000	±500	PTP Bipolar	LCC	Adjacent - New Tower
Variant C	530	1,500	±400	PTP Bipolar	LCC/VSC	Existing - New Tower
Variant D	530	3,000	±500	PTP Bipolar	LCC	Existing - New Tower

The following sections present the criteria taken into consideration for the analysis and design of the variants. From Table 4, it can be seen that variants A and B propose a purely DC link adjacent to the existing lines while variant C and D intend a hypothetical design because they suggest the sharing of the corridors, creating a connection with a hybrid AC/DC corridor. Consequently, some calculations were not performed for variants C and D, and certain parameters are assumed in the design, which should be studied in depth technical analysis outside the scope of this thesis.

3.3. DETERMINATION OF CONDUCTOR

The design of the link included the optimization of the conductors, considering applicable international standards. The bipolar HVDC link was estimated without metallic return, and the conductors used had to satisfy the following:

- Transmission of the design power at the nominal voltages on the bipolar link without a neutral conductor.
- Transmission of the maximum power overload assumed at 25% for the pole operation over ground return.
- Offer safety of the link considering the mechanical loads from wind and icing.
- Offer acceptable rates concerning radio interference, audible noise and corona loss.

Then, the conductor selection involved the choice of suitable conductor in accordance with the operating voltage, the power to be transmitted, the acceptable voltage drop and losses.

VOLTAGE DROP CONSIDERATIONS

For a single pole configuration, the maximum power to be transferred assuming a 10% drop restriction voltage was given by Equation (5) [20]:

$$P_{max} = \frac{\%V_{drop}V^2}{R_{DC}L} \tag{5}$$

Where:

V = Sending end voltage, pole to ground.
$\%V_{drop}$= Percentage of drop in voltage.
R_{DC} = DC resistance of the conductor.
L = Distance.

The rated values of the bipolar line under consideration were 1,500 MW and 3,000MW. So during, one pole outage, the healthy pole should carry up to 25% overload with maximum 10% drop voltage, and according to Equation (5) the pole resistance needed to be less than:

Variant A, C:

$$R_{DC} = \frac{0.1 \times (400kV)^2}{(937.5\ MW) \times (530km)} = 0.032201\ {}^{\Omega}/_{km}$$

Variant B, D:

$$R_{DC} = \frac{0.1 \times (500kV)^2}{(1{,}875\ MW) \times (530km)} = 0.025157\ {}^{\Omega}/_{km}$$

Later, for variants A and C allowing up to maximum of 4 conductors per pole, it was obtained that 0.032201Ω/km×4 = 0.128805 Ω/km which indicated that the conductors with electrical resistances lower than 0.128805 Ω/km should be selected for further study. While for the variant B and D, if 0.025157Ω/km×4 = 0.100628 Ω/km, the conductors with electrical resistances lower than 0.100628Ω/km should be considered.

CURRENT CAPACITY CONSIDERATION

The required current carrying capacity of the designed line was calculated by:

$$Current\ carrying\ capacity\ for\ pole = \frac{P_{max}}{V} \tag{6}$$

While in the bundled conductor pole chosen, each conductor was to carry a current given by:

$$Current\ carrying\ capacity\ per\ each\ conductor = \frac{P_{max}}{nV} \tag{7}$$

Where:

P_{max}= Maximum power capacity of the pole.
V = Sending end voltage, pole to ground.
n = Number of conductors in the bundle.

The required current carrying capacities were calculated using the equations (6) and (7), and the results are shown below.

TABLE 5: POLE CURRENT CARRYING CAPACITY REQUIEREMENT.

Maximum capacity of the pole	Maximum Current Carrying Capacity per pole	Maximum Current Carrying Capacity per each conductor		
		2	3	4
937.5 MW; 400 kV	2,344 A	1,172 A	781 A	586 A
1,875 MW; 500 kV	3,750 A	1,875 A	1,250 A	938 A

Corona Loss, Radio Interference and Audible Noise Considerations

The radio interference, audible noise and corona loss of the conductors are dependent on the surface voltage gradients of the conductors. Therefore, for the variant A and B, I calculated the surface voltage gradient of the selected conductors in view of different bundle arrangements to get a conductor with a surface voltage gradient equal or lower than the acceptable surface voltage gradient for a long transmission line which is approximately 22 kV/cm [4, 12].

For variant C and D these calculations were not performed because it is a hypothesis that the same electric corridor can be shared. However, if this could be achieved, the behavior of the conductor and therefore the calculations of the surface voltage gradient are more complex for a hybrid line than for the individual AC or DC lines. Then, for the design of variant C and D, the selection of the conductor was considered due to its capacity, but some contemplation had to be made as the separation space between the AC/DC circuits as will be shown later.

a) Conductor Surface Gradient

Calculations of voltage gradients of the conductor for variant A and B were given by [70]:

$$D = \frac{S}{\sin\left(\frac{\pi}{n}\right)} \tag{8}$$

$$deq = D\left(\frac{nd}{D}\right)^{\frac{1}{n}} \tag{9}$$

$$F = \left(1 + \left(\frac{2H}{P}\right)^2\right)^{\frac{1}{n}} \tag{10}$$

$$T = \frac{4 * H}{d_{eq}} \tag{11}$$

$$E_{av} = \frac{2V}{100 * nd \ln\left(\frac{T}{F}\right)} \tag{12}$$

$$E_{max} = E_{av}\left(1 + \frac{d(n-1)}{D}\right) \tag{13}$$

Where:

V= DC pole voltage with respect to ground in kV
S= Conductor spacing in m.
H= Mean height of the conductor in m.
P= Pole to pole spacing in m.
n= Number of conductor.
d= Conductor diameter in m.
D= Bundle diameter in m.
d_{eq}= Equivalent bundle diameter in m.
E_{av} = Average conductor gradient (kV/cm).
E_{max} = Maximum conductor gradient (kV/cm).

I applied the following assumptions to calculate the surface gradient voltage of the selected conductors.

TABLE 6: DESIGN PARAMETERS FOR SURFACE VOLTAGE GRADIENT CALCULATIONS.

Variant	A	B
Voltage (V)	400 kV	500 kV
Bundle Spacing (S)	0.457 m	0.457 m
Mean high of conductor (H)	13 m	20 m
Pole to pole spacing (P)	15 m	16 m

In Annex E, it is presented the results of calculations of surface voltage gradient of the selected conductors respect to its electrical resistance. The comparison was made with bundles of 2, 3 and 4 conductors and the results show that the most efficient way to reduce the surface voltage gradient of the DC lines is to increase the number of sub-conductors and place the conductors further apart. In the following table, it is presented the conductor that could be considered for the final variants and further analysis.

TABLE 7: RESULTS FOR SURFACE VOLTAGE GRADIENT.

Variant	Conductor	Diameter (d) (mm)	E_{max} (kV/cm)		
			2	3	4
A	ACSR FALCON	39.26	**22.48**	16.86	13.70
B	ACSR FALCON	39.26	27.36	**20.07**	16.10

b) Corona Loss Performances

In [20], an empirical formula for corona losses in bipolar lines has been expressed, and it was applied in this analysis, where the results are presented in Table 8.

In fair weather conditions,

$$P = 2.9 + 50\log\left(\frac{E_{max}}{25}\right) + 30log\left(\frac{d}{3.05}\right) + 20\log\left(\frac{n}{3}\right) - 10\log\left(\frac{HP}{225}\right) \qquad (14)$$

And in foul weather conditions,

$$P = 11 + 40\log\left(\frac{E_{max}}{25}\right) + 20log\left(\frac{d}{3.05}\right) + 15\log\left(\frac{n}{3}\right) - 10\log\left(\frac{HP}{225}\right) \qquad (15)$$

Where:

P =Corona loss in dB above 1W/m.

E_{max} = Maximum bundle gradient in kV/cm.

d =Conductor diameter in cm.

n = Number of sub-conductors in the bundle.

H= Mean conductor height in m.

P = Pole spacing in m.

The corona power loss in kW/km was given by:

$$P = 10^{\frac{P_{dB}}{10}} \qquad (16)$$

TABLE 8: RESULTS OF CORONA POWER LOSSES.

Variant	Conductor	n	E_{max} (kV/cm)	Corona Losses		
				fair weather	foul weather	worst case
A	ACSR FALCON	2	22.48	1.25 kW/km	**8.55** kW/km	9.06 MW
B	ACSR FALCON	3	20.07	0.97 kW/km	**6.08** kW/km	6.44 MW

c) Radio interference and audible noise

According to [20], no limits currently exist for radio interference (RI) and audible noise (AN) level for HVDC transmission lines. The same source gives an empirical formula for radio interference (RI) in bipolar lines and average fair weather at a radial distance of 30 m from the positive conductor to the measuring point as follows:

$$RI = 51.7 + 86log\left(\frac{E_{max}}{25.6}\right) + 40\log\left(\frac{d}{4.62}\right) \qquad (17)$$

Where:

E_{max} = maximum bundle gradient in kV/cm.

d =conductor diameter in cm.

The L_{50} fair weather audible noise (AN) of a DC line was given as:

$$AN = AN_0 + 86\ log(E_{avg}) + klog(n) + 40\log(d) - 11.4\log(R) \qquad (18)$$

Where:

E_{avg} = average maximum bundle gradient in kV/cm.
n =number of sub-conductors.
d = conductor diameter in cm.
R = radial distance from the positive conductor to the point of observation in m (generally the protective zone boundary, 30 m).
k = 25.6 for n > 2; k=0 for n = 1, 2;
AN_0 = -100.62 for n > 2; AN_0 = -93.4 for n=1, 2

TABLE 9: RESULTS RADIO INTERFERENCE AND AUDIBLE NOISE AT 30 M.

Variant	Conductor	n	E_{ave} (kV/cm)	E_{max} (kV/cm)	k	AN_0	RI	AN
A	ACSR FALCON	2	20.70	22.48	0	-93.4	44.02dB	26.69dB
B	ACSR FALCON	3	17.47	20.07	25.6	-100.62	39.78dB	25.35dB

CURRENT AND POWER CARRYING CAPABILITY

To estimate the current carrying capability of conductors, I used the CIGRE recommendation on thermal behavior of overhead conductors [71]. The thermal state of overhead conductors mainly depends on external parameters, like wind speed and direction, temperature and solar irradiance, as well as on the electrical load circulating through it. Taking that all these parameters remain relatively constant, the conductor can be considered as in a steady state, and its temperature remains reasonably constant.

Under steady state condition, the heat supplied due to electric current and the solar radiation is balanced by the heat dissipated by wind and radiation. The heat balance equation can then be written as:

$$P_J + P_M + P_S + P_i = P_c + P_r + P_w \qquad (19)$$

Where:

P_J = Joule heating.
P_M = Magnetic heating.
P_S = Solar heating.
P_i = Corona heating.
P_c = Convective cooling.
P_r = Radiative cooling.
P_w = Evaporative cooling.

Most of the time the heat gain due to corona and the heat loss due to evaporation may both be significant when there are precipitations, but for rating purposes they are rarely relevant, and it is suggested that the terms P_i, P_M and P_w in equation 8 be neglected.

$$P_J + P_S = P_c + P_r \qquad (20)$$

a) Current Heating: The value of the Joule heat gain per unit length for conductors carrying direct current was found from the equation:

$$P_J = I_{dc}^2 R_{dc}\left[1 + \alpha(T_{avg} - 20)\right] \qquad (21)$$

Where:

I_{dc} = Effective direct current.
R_{dc} = DC resistance per unit length.
α = Temperature coefficient of resistance per degree Kelvin.
T_{avg} = Mean temperature of the conductor.

b) Solar Heating: The solar heating using global solar radiation can be written as:

$$Ps = \alpha_s SD \quad (22)$$

Where:

α_s = Absorptivity of conductor surface, varies from 0.23 to 0.95.
S = Global solar radiation.
D = External diameter of the conductor.

c) Convective Cooling: The convection is usually the most important factor for cooling overhead conductors. Convention cooling taking place with two conditions when the wind speed is zero, it is a natural convention and when there is the wind, forced convention. The convective heat loss can be expressed as a function of the Nusselt number, by the following formula:

$$P_c = \pi\lambda_f(T_s - T_a)\, Nu \quad (23)$$

Where:

λ_f = Thermal conductivity.
T_s = Temperature of the surface of the conductor.
T_a = Ambient temperature.
Nu = Nusselt number.

d) **Radiative Cooling:** The radiative heat loss from a conductor was given by the following equation:

$$P_r = \pi D\varepsilon\sigma_B[(T_s + 273)^4 + (T_a + 273)^4] \quad (24)$$

Where:

D= External diameter of the conductor.
ε = Emissivity of the surface of the conductor varies from 0.23 - 0.95.
σ_B = Stefan-Boltzmann constant.
T_s = Temperature of the surface of the conductor.
T_a = Ambient temperature.

From equation (20) and (21) it can obtain the current carrying capability of conductors by:

$$I_{dc} = \sqrt{\frac{P_c + P_r - P_S}{R_{dc}[1 + \alpha(T_{avg} - 20)]}} \quad (25)$$

Then, the assumptions that I applied for the analysis of the conductors respect to their thermal behavior on steady state are presented in Table 10, and the results on Table 11.

TABLE 10: DESIGN PARAMETERS FOR STEADY STATE.

Height above sea level (y)	430 m a.s.l.
Global solar radiation (S)	1,000 W/m^2
Wind velocity (v)	0.6 m/s
Wind angle (δ)	90°
Ambient temperature (T_a)	30°C
Temperature coefficient (α)	0.00403 K^{-1}
Stefan-Boltzmann constant (σ_B)	$5.67 \times 10^{-8}\, W/m^2K^4$
Emissivity of the surface of the conductor (ε)	0.5
Absorptivity of conductor surface (α_s)	0.5
Highest conductor temperature (T_s)(T_{avg})	75°C

TABLE 11: RESULTS OF CONDUCTOR CURRENT CARRYING CAPACITY DURING STEADY STATE.

Conductor	P_c (W/m)	P_r (W/m)	P_s (W/m)	Current Carrying Capacity per each conductor, I_{dc} (A)
ACSR FALCON	67.75	21.81	19.63	**1,271**

From the result, ACSR FALCON conductor has a capacity of 1,271 A for DC current given the assumed conditions. From manufacturer catalog (Annex E), the rated current carrying capacity of the ACSR FALCON conductor is 1,510 A. Thus; it can be injected a DC current near to the thermal limit of the conductor. Later, the results of the maximum pole carrying capacity under the above conditions are presented in Table 12.

TABLE 12: RESULTS OF THE POLE CARRYING CAPACITY.

Variant	Conductor	Current Carrying Capacity per each conductor, I_{dc} (A)	Bundle	Pole carrying capacity (MW)
A, C	ACSR FALCON	1,271	2	**1,017**
B, D	ACSR FALCON	1,271	3	**1,907**

Finally, I selected the ACSR FALCON with two sub-conductors per pole as the most suitable solution for the variant A and C, while the ACSR FALCON with three sub-conductors per pole for the variant B and D of the HVDC link, in view of the above conditions.

3.4. SPAN, CONDUCTOR CONFIGURATION AND CLEARANCE

For the variants A and B, I adopted the following arrangement:

- A flat conductor configuration.
- The span of 350 m.
- The additional width of existing ROW.

In the other hand, the variants C and D presented distinctive characteristics. It was difficult to implement a general configuration and I considered that each new tower was coupled to the existing tower in the corridor and designed keeping as much as possible the characteristics of this one so as not to create a conflict between powerlines, as well in order to reuse the shield wires if it is possible and share ROW. Therefore, based on given data [78], the assumed arrangement was:

- A flat conductor arrangement.
- The span of 239 m between Röhrsdorf and Hradec.
- The span of 316 m between Hradec and Chrást.
- The span of 336 m between Chrást and Kočín.
- The span of 265 m between Kočín and Slavětice.
- The span of 322 m between Slavětice and Dürnrohr.

The variants C and D are more complicated for design, construction, and management because were developed supposing as an idea of a hybrid corridor AC/DC as the case of Südlink ULTRANET but using different towers. These variants must be completely studied regarding its technical feasibility, which it is beyond the scale of this thesis. Therefore, here is presented as an estimated possible alternative.

3.5. APPROXIMATE SAG -TENSION CALCULATIONS

During the erection of OHL, the conductors are connected to two towers. The conductors must be connected with the proper tension because if they are connected very tightly, the tension on the conductor could be very high and at some point, it may break. In the other hand, if they are connected very slack, the charging current increases the length of conductor and also this provokes that the height of the tower structure increase. Therefore, the conductors must be connected in such a way that the tension is ideal and at the same time there should be proper clearance between the ground and the conductor.

Hence, it was necessary to determine the sag for the design of the variants involved because it determines the value of safe working tension, the minimum clearance of the conductor about ground and height of the towers. Calculations of sag-tension are usually performed with the assistance of a computer; however, with certain simplifications, these calculations can be made with a handheld calculator [6]. This approach helped for a better understanding of the calculations of sag and tensions for the approximation in the height of support structures.

If it is considered a fairly flat terrain, the supports are at equal levels, and under normal conditions (i.e. at normal temperature and the weight acting on the conductor is only its weight), the equations for calculations are given by [6, 56].

The sag of the conductor can be calculated by:

$$S = \frac{wl^2}{8T} \quad (26)$$

Where:

w = Weight per unit length of the conductor.
l =Length of span.
T = Tension in the conductor.

The conductor length can be calculated from:

$$L = l + \frac{8S^2}{3l} \quad (27)$$

Where:

l =Length of span.
S = Sag of conductor.

But when the conductor is covered with ice and/or is exposed to the wind, the conductor weight per unit of length increases. During a time of thick ice and/or wind load, the conductor catenary tension increases along with the loads on structures [56]. Both the conductor and its support can fail unless these high tensions are considered in the line design. Therefore, it was analyzed the boundary conditions given on [5, 57] to approximate the value of sag-tensions in the selected conductor. The parameters and relations applied to simplify this analysis are given by [56, 57].

The static component of the wind load (w_w) acting perpendicular to the conductors was determined from the equation:

$$w_w = P_w(D + 2t) \quad (28)$$

Where:

P_w = Wind pressure load on conductor.

D = Overall diameter of the conductor.
t = Thickness of ice.

The wind pressure (P_w) was determined from the equation:

$$P_w = P_o k_w C_w \tag{29}$$

Where:

P_0 = Basic wind pressure, in the Czech Republic is 550 Pa.
k_w = Coefficient of height.
C_w = Coefficient of uniformity.

Then to estimate the total weight of the conductor (i.e., both the conductor weight and the weight of the ice acts vertically down while the wind force acts horizontally on the conductor), it was applied the following equations.

The total weight of conductor (w_t) was determined from the equation:

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2} \tag{30}$$

Where:

w = Weight of conductor per unit length.
w_i = Weight of ice per unit length.
w_w = Wind load per unit length.

The conductor sets itself in a plane at an angle to the vertical where:

$$\tan\theta = \frac{w_w}{w + w_i} \tag{31}$$

Where:

w = Weight of conductor per unit length.
w_i = Weight of ice per unit length.
w_w = Wind load per unit length.

The sag in the conductor was given by:

$$S = \frac{w_t l^2}{8T} \tag{32}$$

Where:

w_t = Total weight per unit length of the conductor.
l = Length of span.
T = Tension in the conductor.

The vertical sag was obtained applying the following relation:

$$S_y = S\cos\theta \tag{33}$$

Where:

S = Sag in the conductor.
θ = Angle between sag and vertical.

Taking into account that the environmental conditions during the erection of the line are different from the worst design conditions of the line, a relationship equation (34) between the two conditions is derived in [12, 14], and I applied it to facilitate the calculation of the tension.

$$T_2{}^2\left[T_2 - \left\{T_1 - \alpha AE(\theta_2 - \theta_1) - \frac{AEF_{t1}{}^2 l^2}{24T_1{}^2}\right\}\right] = \frac{AEF_{t2}{}^2 l^2}{24} \quad (34)$$

Where:

T_1 = Tension under the worst probable conditions.
θ_1 = Temperature under the worst probable conditions.
F_1= Total load per length under the worst probable conditions.
T_2 = Tension under the erection conditions.
θ_2 = Temperature under the erection conditions.
F_2= Total load per length under the erection conditions.
l = Length of the span.
A = Cross sectional of the conductor.
E = Modulus of elasticity of the conductor.
α = Coefficient of linear expansion.

Using this derived equation erection tension T_2 was determined such that the tension under worst probable conditions T_1 will not exceed the safe limit of tension, namely 50% of rated strength of the conductor. The sag for erection conditions was then calculated using this value of tension. For the calculation of deflection and tension of the conductors, I considered the following cases as probable conditions to determine the maximum permissible tension:

- -30 ° C, no wind and no icing.
- -5 ° C, wind on frosted wire.
- -5 ° C, no wind and normal icing at relevant area.
- -5 ° C, wind on non-frosted wire.

TABLE 13: DESIGN PARAMETERS SAG-TENSION ANALYSIS.

Conductor type	ACSR FALCON
Conductor overall diameter (D)	39.26 mm
Conductor cross section (A)	908.6 mm^2
Conductor unit mass (m_{cod})	3.04 kg/m
Rated strength of the conductor	242.51 kN
Modulus of elasticity (E)	68,000 N/mm^2
Coefficient of linear expansion (α)	$19.4 \times 10^{-6} 1/°C$
Maximum wind velocity (v)	33.5 m/s
Wind Pressure (P_0)	550 Pa
Ice Thickness (t)	27.6mm
Ambient Temperature of reference (θ_2)	25 °C

The erection tension was first estimated, then sag(s) was calculated for each section of the whole link in view of the above-enlisted conditions, Table 13 and Annex G. The results gave an approximate erection tension but most important an estimated value of sag, and this parameter was needed in order to suggest the height of the support structure of the line. The results of this analysis are presented on Annex G.

3.6. INSULATION CONFIGURATION

Regarding the insulation configuration for the variants:

- Considering the contamination level, I assumed the creepage distance to be at least 40 mm/kV, according to IEC 60815 [13, 72].

- A possible length of suspension insulator string could be 5.0m for a composite type or 6.18m for porcelain type for systems at ±400kV [73]. However, for systems at ±500kV, it is suggested 6.6m [16] and 7.33m for composite Long-rod [73]. Examples of insulator lengths used on operating lines and test lines for HVDC are shown in the diagram below.

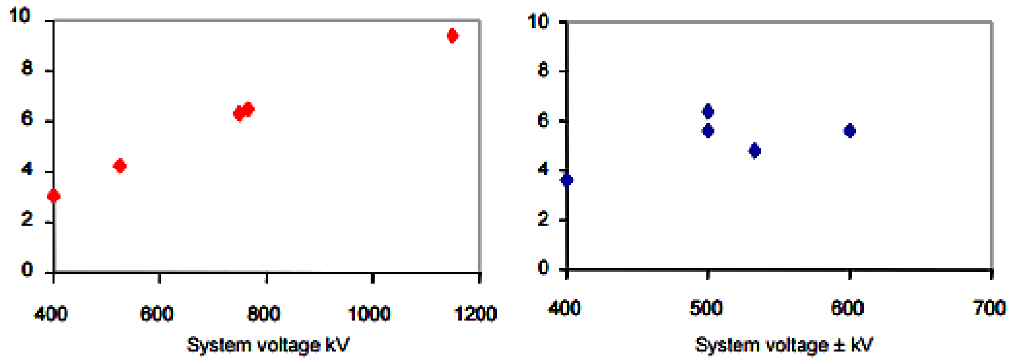


FIGURE 19: ACTUAL INSULATOR LENGTHS IN METER AT DIFFERENT SYSTEM VOLTAGES FOR EHVAC AND HVDC [63].

- With HVDC, the switching overvoltage are lower, in the range 1.6 to 1.8 p.u. and the air clearance is frequently determined by the required lightning performance of the line [63]. As shown in Figure 20 for the ±400kV systems an air clearance of at least 2.2m is necessary and at least 3m for the ±500kV systems.

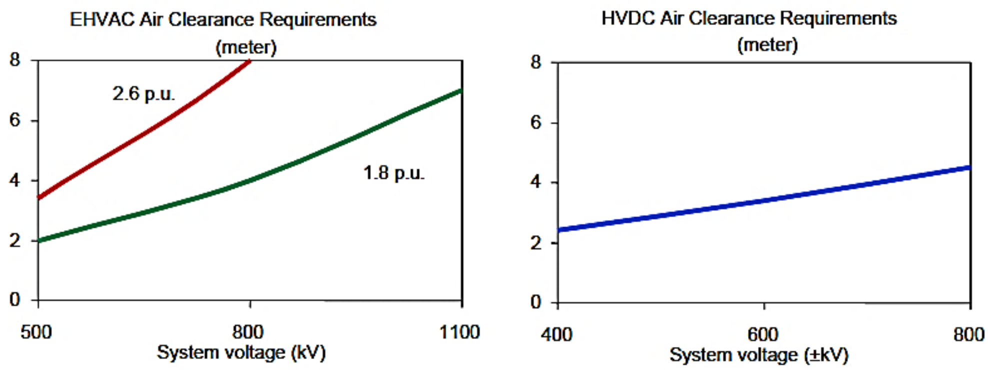


FIGURE 20: AIR CLEARANCE REQUIREMENTS FOR EHVAC AND HVDC [63].

- The Guide for EHV Line Shielding Angles proposed by Armstrong and Whitehead recommends that *"the shielding angle for an average shield wire height above soil of more than 35m and vertical type of towers is to be less or equal to 0°"* [12]. Consequently, I supposed that:
  - One earth-wire for the variant A and B, while two earth wires for the variant C and D subtending an angle approximated to 0° to the current carrying conductors at the tower could be incorporated into the design.
  - The minimum distance between live conductors and shield wire needed to be at least 10 m for towers.
  - The sag of shield wire should be 10% less than the sag of current carrying conductor. Thus the sags of the shield wire must be not more than 90% of the sag of the conductors at their respective sections.

3.7. LINE SUPPORTS

LINE SUPPORT FOR VARIANT A

The following parameters based on previous results were contemplated for the scheme of the line support structure:

- Cross-arm length = 7.5 m (15 m conductor spacing).
- Insulation length = 5.0 m
- Maximum conductor sag, S=8.10 ≈ 9.0 m
- Conductor clearance = 13.0 m
- Spacing between shield and live conductors = 10 m

As a result, the total tower height was 32 m, that is:

$$Total\ tower\ height\ =\ 13m\ +\ 9m\ +\ 10m\ =\ 32m$$

Since a span of 350 m was adopted, the total number of towers required for the whole link was estimated as follows:

$$Number\ of\ towers\ = \frac{530\ km}{350\ m} = 1{,}514$$

LINE SUPPORT FOR VARIANT B

The following parameters based on preceding results were used for the scheme of the line support structure:

- Insulation length = 7.0 m
- Cross-arm length = 8.0 m (16 m conductor spacing).
- Maximum conductor sag, S=8.10 ≈ 9.0 m
- Conductor clearance = 20.0m
- Spacing between shield and live conductors = 13.6m

The total tower height was 42.6 m and the estimated amount of towers was 1,514.

LINE SUPPORT FOR VARIANT C

The hypothetical variant C suggested corridor sharing, and the existing lines use mostly Dunaj towers for double circuits and Kočka towers for single circuits. But considering that in the future those single circuits can be doubled, most of the towers would be Dunaj type, so the towers for the DC link should be suggested with sufficient space to avoid creating a conflict between AC circuits and DC.

The following parameters based on results were considered for the line support structure of variant C:

- Insulation length = 5.0 m
- Cross-arm length = 17.5 m (35.0 m conductor spacing)
- Maximum conductor sag, S = 8.0 m
- Conductor clearance = 21.7 m
- Spacing between shield and live conductors = 10.6 m

The total tower height was 40.3 m and the estimated amount of towers was 1,800.

LINE SUPPORT FOR VARIANT D

The hypothetical variant D also suggested corridor sharing, but this variant was planned for a high voltage level; therefore I decided to increase the height of the towers, then the DC circuit will be above the AC circuits. The design parameters of the line support structure of this variant:

- Insulation length = 7.0 m.
- Cross-arm length = 8.0 m (16.0 m conductor spacing).
- Maximum conductor sag, S = 8.0 m
- Conductor clearance = 31.70m
- Spacing between shield and live conductors = 13.6m

The total tower height was 53.30 m and the estimated amount of towers was 1,800.

In Annex H, the sketches with the dimensions that were calculated previously are presented. The black structures correspond to pylons with general dimensions shown in [85] for AC systems, and which in this case simulate the existing electric corridor. In contrast, red structures represent the suggested structures for the link; they correspond to typical self-supporting suspension tower configuration for HVDC OHL; and the dimensions calculated for variants with a parallel corridor (A.1, A.2 and B) as well as for variants hypothetically sharing the electric corridor (C.1, C.2, and D).

For the suggested structures, the variants A and B indicated a typical design existing in the market, while for alternatives C and D must be adapted to the requirements to share the space, therefore will be higher or wide, which may affect the cost of variants C and D. But as mentioned above, DC support structures usually require less material because they should not support as many conductors as an AC system for the same power capacity so their cost can also be impacted for this too. Also, the actual number of towers could be slightly lower than these values because the span chosen had to increase where the line crosses rivers, streets or highways.

3.8. Converter Stations

For the design of the point-to-point bipolar transmission line, two stations were planned at each end of the link. During normal operating conditions I assumed that the rectifier station was located in Röhrsdorf, Germany; while in Dürnrohr, Austria the inverter station was located. As shown in Table 4 in Section 3.2, the variants would also comprise two different types of technologies, i.e. VSC and LCC since the ratings for those HVDC systems are available (Figure 21).

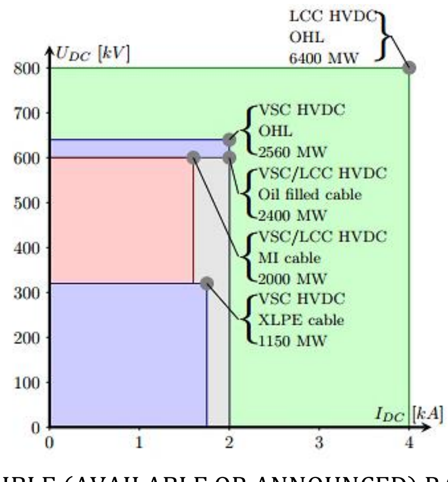


FIGURE 21: CURRENT POSSIBLE (AVAILABLE OR ANNOUNCED) RATINGS FOR HVDC SYSTEMS (U_{DC} REFERS HERE TO THE POLE VOLTAGE, IN A BIPOLAR SETUP, $P = 2 \cdot U_{DC} \cdot I_{DC}$) [74].

LCC system is superior to self-commutating VSC transmission regarding capital cost, power losses, and reliability for large-scale HVDC transmission. However, the main disadvantage of LCC converter is that it operates with lagging power factor, consuming a reactive power up to 50% of active power [11, 28, 74].

On the other hand, VSC is a newer technology compared to LCC. It has several advantages such as its ability to provide reactive power support; independently power control or its ability to restart an AC network in the event of a blackout scenario. Another notable characteristic is that since the power flow is reversed without changing the polarity of the DC voltage and since the IGBT valves do not suffer from switching faults, the VSC technology is in principle suitable for multiterminal applications. However, its main disadvantages are the expensive capital cost and lower available ratings [11, 75].

Calculations were not developed referent to the converter station equipment since available ratings, and consequently, the typical cost of these facilities was used to facilitate calculations. So the variants will have the following characteristics:

TABLE 14: SUMMARY OF CONVERTER STATION.

	LCC		VSC
Power Transmission	1,500 MW	3,000 MW	1,500 MW
Voltage Level	400 kV	500 kV	400 kV
Load Losses[10, 74]	0.7 – 0.8 %		1 – 1.7%
No Load Losses [10]	0.11%		0.2 %

4. Economic Evaluation

This section considers an economic analysis for an HVDC system, so I tried to estimate the costs relating to the converter stations, transmission lines, Joule losses, converter stations losses, operating and maintenance expenses of both lines and stations. It is important to mention that this section does not have reliability calculations due to the lack of information for certain technologies under consideration.

4.1. Cost Estimation

The cost of an HVDC system depends on many aspects such as power capacity, voltage, the transmission medium (cable or OHL), environmental conditions, regulatory framework, etc. Although options exist, the alternatives available for optimal design (different commutation techniques, diversity of equipment, etc.), it is hard to give a cost figure for an HVDC system.

As for the basic design of the variants, it was tried to employ available ratings, the methodology used for estimating costs was based on literature data from existing projects as well as reference of manufacturers and study reports from different sources such as [69, 74, 76, 77, 79]. Thus, the assumed figures can vary and even push out the estimated average due to parameters such as local market prices of raw material; electricity cost; new developments and available infrastructures for example.

4.1.1. Converter Stations

The station cost includes all the investments required in the installation of equipment to be applied in a point-to-point configuration, excluding the high voltage transmission line. A typical cost structure for the converter stations could be as follows in Figure 22.

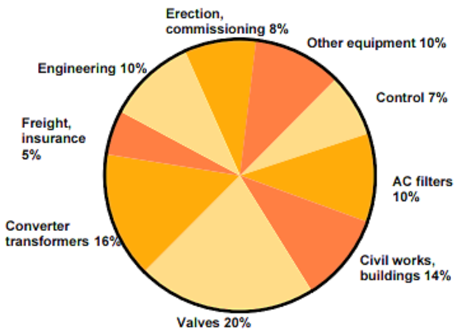


FIGURE 22: TYPICAL COST STRUCTURE OF CONVERTER STATION [19].

For this analysis was taken the CIGRE reference from the working group B4.46 [74]. This reference provided a specific cost of 0.102 M€/MW used for all power ratings and voltage levels for VSC-HVDC station and the Italy-Greece HVDC link as a reference for LCC-HVDC station cost of 0.08 M€/MW. As for, operating and maintenance expenditure were outlined as 0.5% of investment costs per year per terminal.

TABLE 15: OUTLAYS OF CONVERTER STATIONS [74, 76].

	LCC	LCC	VSC
Power Rating	1,500 MW	3,000 MW	1,500 MW
Voltage Rating	±400 kV	±500 kV	±400 kV
Investment Cost (million CZK per terminal)	3,000.00	6,000.00	3,825.00
O&M Cost (million CZK per terminal)	15.00	30.00	19.13

4.1.2. TRANSMISSION LINE

The cost of a point-to-point connection depends on several factors such as political and environmental framework, the cost for the rights-of-way, construction cost payments for environmental impact, labor costs and compensations for the right of way usage. Especially the geographical conditions have an impact on the expenses. In this section, the construction costs are the central point.

The HVDC overhead transmission line costs were estimated based on the HVAC cost with respect to lower conductors, insulators and support structure costs and equal payments for civil works, project planning, etc. According to [20, 74] a cost ratio between 0.75 and 1 could be used to estimate HVDC OHL transmission line investment cost.

For variants A and B, I used a cost ratio 0.8 due to these variants have smaller structures along the corridors and do not need dismantling process. While for variants C and D, I applied a cost ratio of 1 to reflect the complex characteristics of the design of the support structures (i.e. taller and wider pylons) as well some process of dismantling and bypassing of the existing powerlines could be needed for the construction. Also, a 1% of the investment cost was assumed for the operation and maintenance cost of all variants.

The costs for HVAC overhead transmission lines were taken from the construction of a new 400 kV single circuit line Krasíkov – Horní Životice and doubling the existing 400 kV line Výškov – Čechy Střed with bundled conductors. The costs were estimated to be 25 and 30 million CZK/km [58].

TABLE 16: OUTLAYS OF TRANSMISSION LINE.

Variant	Investment Cost	O&M Cost
A	20 million CZK/km	0.20 million CZK/km
B	24 million CZK/km	0.24 million CZK/km
C	25 million CZK/km	0.25 million CZK/km
D	30 million CZK/km	0.30 million CZK/km

4.1.1. RIGHT OF WAY

The appreciation of rights of way was very complicated; thus only the space requirement during the operation was considered in this estimation since only for the permanently occupied space payment has to be paid to the land owners. For the evaluation of the right of way, these observations were considered:

- The variant A and B need the increase of existing corridor.
- The variant C and D shared of the ROW of the existing powerlines.

Regarding an overhead transmission line there is the width of the tower construction as well as a protective zone on both sides (i.e. 30 m from the outer conductor for systems at 400kV and above) which has to be accounted. As an approximated the cost amount to 20 – 24 CZK/m^2 as a single payment.

TABLE 17: OUTLAYS OF RIGHT OF WAY.

Variant	Required ROW	Outlay
A	75 m	954.00 million CZK
B	76 m	966.72 million CZK
C, D	-	-

4.1.2. LOSS EVALUATION

For the evaluation of DC losses, in addition to the pure losses dependent on the current of the conductor, I also considered the losses of the converters stations but line corona losses were not included for simplification, and its impact in the result is small agreeing with [79]. For these calculations, it was assumed the losses to be linear. Table 18 describes the parameters used for the HVDC link.

TABLE 18: POWER LOSSES.

Variant	A, C		B, D
Pole cross section (mm²)	1,817.20		2,725.80
Resistance per pole (Ω/km)	0.017715		0.01181
Specific resistance at 20°C (Ω*mm²/m)	0.0322		0.0322
Transmission power (MW)	1,500		3,000
Voltage (kV)	±400		±500
Current (A)	1,875		3,000
Number of DC stations	2		2
Length of line (km)	530		530
DC station technology	LCC	VSC	LCC
No load losses in % of transmission power per DC Station	0.11%	0.2%	0.11%
Load losses in % of operating transmission power per DC station	0.8%	1.7%	0.80%
Line losses (MW)	66.02	66.02	112.67
No load losses (MW)	3.30	6.00	6.60
Station losses (MW)	24.00	51.00	48.00
Total power loss at transmission power (MW)	93.32	123.02	167.27

The power losses obtained from the case of full load can be determined using the expected maximum time usage (Tm) of the link, which was assumed to be 4,000 h/year. Therefore, the annual energy losses are shown in Table 19 yield from following calculations.

$$T_z = \left[0.2\left(\frac{T_m}{8760}\right) + 0.8\left(\frac{T_m}{8760}\right)^2\right] 8{,}760 \quad (35)$$

Where:

T_m = Maximum time usage.
T_z= Full time losses.

$$W_{zr} = P_{zm} * T_z \quad (36)$$

Where:

W_{zr} = Annual energy losses.
P_{zm} = Maximum losses of power.
T_z= Full time losses.

The estimation of the cost of losses was calculated using the electricity cost obtained from [80] that uses the method of Long Run Marginal Cost (LMRC) by representatives. The specific cost calculation was based on the following formula and the inputs parameters given in [80]:

$$n_m(j, T_m, k_m) = p_A\left(n_{pAj} + 8760 n_{wAj}\right) + p_V n_{pVj} + k_m n_{pSj} \quad (37)$$

n_m=0.2862(6,279+8 760*0.366)+0.7138(1,673)+1(222)
n_m=4,131.00 CZK/kW/year

The results of the evaluation of losses were calculated with the above considerations and are presented in Table 19; it can be observed that the losses are greater for the systems that use VSC technology.

TABLE 19: ANNUAL LOSSES.

Transmission power	1,500MW	1,500MW	3,000MW
DC station technology	LCC	VSC	LCC
Line losses (GWh)	149.27	149.27	254.76
No load losses of converter (GWh)	7.46	13.57	14.92
Converter losses (GWh)	54.27	115.32	108.54
Total losses (GWh)	211.01	278.16	378.22
Electricity cost (CZK/kWh)	1.8269	1.8269	1.8269
Cost of losses (million CZK/year)	385.49	508.18	690.98

4.2. Risk and Uncertainties

Any project involves risks and uncertainties, as part of the study; these should also be considered [81]. In transmission line projects, contemporary works found that the main risk categories are:

Technical Risk

- Technical lifetime of the components.
- Errors during installation and construction.
- Quality of materials.
- Failures or exit of the components during operation.

Environmental Risk

- Weather conditions not conducive to the construction and installation, for example wind, storms.
- Impact of weather conditions during operation of the link.
- Rusting in pullery, wire, etc.

Financial Risk

- Project overrun costs.
- Installation delay subcharge.
- Accident inssurance charges.
- Damaged equipment costs.
- Increase in wages and salary.
- Foreign exchange risk.
- Interest rate risk.
- Adverse laws and regulations.

Human Risk

- Electrical discharge from powerline.
- Unskilled workers.
- Faulty safety clearence.

HR management risks

- Team work skills.
- Quick decision ability.
- Deadline handling ability.
- Labor and supplier issues handling ability.

FIGURE 23: MAIN RISK CATEGORIES AND EXAMPLES BASED ON [25]

4.3. Time Considerations

It is also important to identify the time required to start a transmission project of this complexion. The time put in operation can vary and also is strongly dependent on considerations such as environmental framework of the project. So if it is considered a project with a less public opposition, it could be considered a fast approval process and a short construction time of approximately 8 years before commissioning. However, it may also be the case for an increased approval and construction time due to a more sensitive environmental situation that could delay a project until 12 years, before its commission or even canceled.

4.4. Discount Rate and Exchange Rate

The discount rate used for the analysis was selected bearing in mind that for the energy distribution and transmission utilities in the Czech Republic this value is given by the Energy Regulation Board (ERU). This office applies the methodology of weighted average cost of capital (WACC); it sets all input parameters that are fixed for the entire control period, and currently, the value of WACC before tax is 7.95% and after tax is 6.44% [82]. Therefore, during the analysis, I utilized for the evaluation a base case discount rate of 8%.

Also, another input parameter that was used was the exchange rate applied, and I applied a long run exchange rate of 25 CZK/EUR and 20 CZK/USD according to the exchange rates of [59] observed before the intervention to the Czech crown during the years 2015-2017.

4.5. Economic Analysis

4.5.1. Net Present Value

As it has been observed so far, a link using HVDC technology could have multiple design solutions varying its investment cost and operating cost scenarios. Consequently, apart from comparing the different options from the technical point of view, there is also the need to select an optimum cost solution. Usually, to achieve this, investment cost options could be calculated and compared, and if it is technically adequate, the lower investment cost option is mostly selected. However, if somehow the solution with lower investment cost requires higher operating cost, then this solution might not be the cheapest and optimal solution if it is considered the useful life of the project. This lead to using a comparison of lifecycle cost to make a reasonable decision on the least cost project.

Therefore, for the comparison of the variables, it was used the net present value measure. The net present value (NPV) is the difference between the initial investment and the present value of the cash inflows and outflows. Inflows are given a positive value while outflows are assigned a negative value. In comparing alternatives, the one with the highest net present value is the best investment [3].

In this case study, firstly all cash flows were considered outlays in order to estimate the net present cost of each of the variants [9]. For the realization of the investment cost, it was used all the investment outlays like previous studies, investments for converter stations and transmission line, and outlays associated with the rights of way, while for the operating cost, it was considered the cost of energy losses and operating and maintenance cost.

From the summary presented in Table 20, it gives the idea that the investment cost of the converter stations for the LCC solutions is lower than the VSC alternatives; and the cost of the losses of the LCC link is lower than the VSC ones for the same capacity.

The key input parameters for the analysis are summarized as follows:

- Discount rate: 8%.
- Period of analysis: 8 years of approval and construction, and 30 years in operation.
- Considering a representative 8% of the investment cost of converter stations and the transmission line for previous studies, spread over the first 4 years of the period of approval and construction (2% per year).

TABLE 20: SUMMARY OF VARIANTS AND INVOLVED OUTLAYS.

	A.1 LCC-OHL	A.2 VSC-OHL	B LCC-OHL	C.1 LCC-OHL	C.2 VSC-OHL	D LCC-OHL
Voltage Rated (kV)	± 400	± 400	± 500	± 400	± 400	± 500
Power Rated (MW)	1,5000	1,5000	3,000	1,500	1,500	3,000
INVESTMENT COST						
Previous Studies (million CZK)	1,328.00	1,460.00	1,977.60	1,540.00	1,672.00	2,232.00
Converter Station (million CZK)	6,000.00	7,650.00	12,000.00	6,000.00	7,650.00	12,000.00
Transmission Line (million CZK)	10,600.00	10,600.00	12,720.00	13,250.00	13,250.00	15,900.00
Right of Way (million CZK)	954.00	954.00	966.72	0.00	0.00	0.00
OPERATING COST						
O&M Station (million CZK/year)	30.00	38.25	60.00	30.00	38.25	60.00
O&M Transmission Line (million CZK/year)	106.00	106.00	127.20	132.50	132.50	159.00
Losses (million CZK /year)	385.49	508.18	690.98	385.49	508.18	690.98

Then, to find an optimum cost solution, the net present value of the options was calculated and compared, using equation 38.

$$NPV = -\sum_{t=-7}^{0} \frac{Inv_t}{(1+r)^t} - \sum_{t=1}^{30} \frac{Op_t}{(1+r)^t} \quad (38)$$

Where:

t = Time of the flow.
r = Discount rate.
Inv_t= Investment cost at time t.
Op_t = Operating cost at time t.

Then, the results are presented in the following table:

TABLE 21: RESULTS OF ANALYSIS.

Variant	A.1 LCC-OHL	A.2 VSC-OHL	B LCC-OHL	C.1 LCC-OHL	C.2 VSC-OHL	D LCC-OHL
Voltage(kV)	± 400	± 400	± 500	± 400	± 400	± 500
Power (MW)	1,500	1,500	3,000	1,500	1,500	3,000
Net Present Value - NPV (million CZK)	-27,123.98	-30,591.15	-40,963.86	-29,421.52	-32,888.69	-43,945.24
Net Present Cost - NPC (million CZK)	**27,123.98**	30,591.15	**40,963.86**	29,421.52	32,888.69	43,945.24
Specific Cost (million CZK/MW)	18.0827	20.3941	**13.6546**	19.6143	21.9258	14.6484

With these results obtained using only the NPC, lead us to that only the similar variants are comparable, i.e. there was a solution with the lowest NPC for variants of 1,500MW and another among the variants of 3,000MW. Then, it was also necessary to obtain the specific cost to be able to compare to all variants. Then:

- When comparing options A and C, it is seen that:
  - The difference between the NPC of variants A.1 and C.1 as well as A.2 and C.2 has been around 7.5% - 8.5% difference respectively, maybe this difference is due to the consideration of increased cost of the transmission line for variants C because of the complication of its construction, which is reflected in the cost ratio assumed for the analysis.
  - It can be observed that variants A.2 and C.2, where VSC technology is used, the net present cost is up to 12.8 % higher if compared to their homologs but applying LCC (i.e., A.1 vs. A.2 and C.1 vs. C.2).
  - Then for the variants of 1,500MW at ± 400kV, the one that implies a smaller NPC would be the variant A.1.

- When comparing options B and D, it is seen that:
  - The analysis has only been done with LCC technology with the ratings available for the capacity of 3,000MW.
  - For these variants, the cost difference has been an approximate 7.3%
  - The variant B: 3,000 MW at ± 500kV has the lowest NPC.

- The option with the lowest specific cost among the six options is the variant B: the overhead line using LCC technology with a capacity of 3,000 MW at ± 500kV.

Also, a sensitivity analysis was performed to evaluate, how the solutions obtained and the objective function would be affected by the change of one of the parameters, keeping the remaining parameters fixed. First, a sensitivity analysis of NPC to the discount rate changes was made as shown in Figure 24. As presented, it can be seen that increasing of discount rate lead to decreasing of NPC, and there is a very slight variation of the net present cost referring to the discount rate between 8% and 12%.

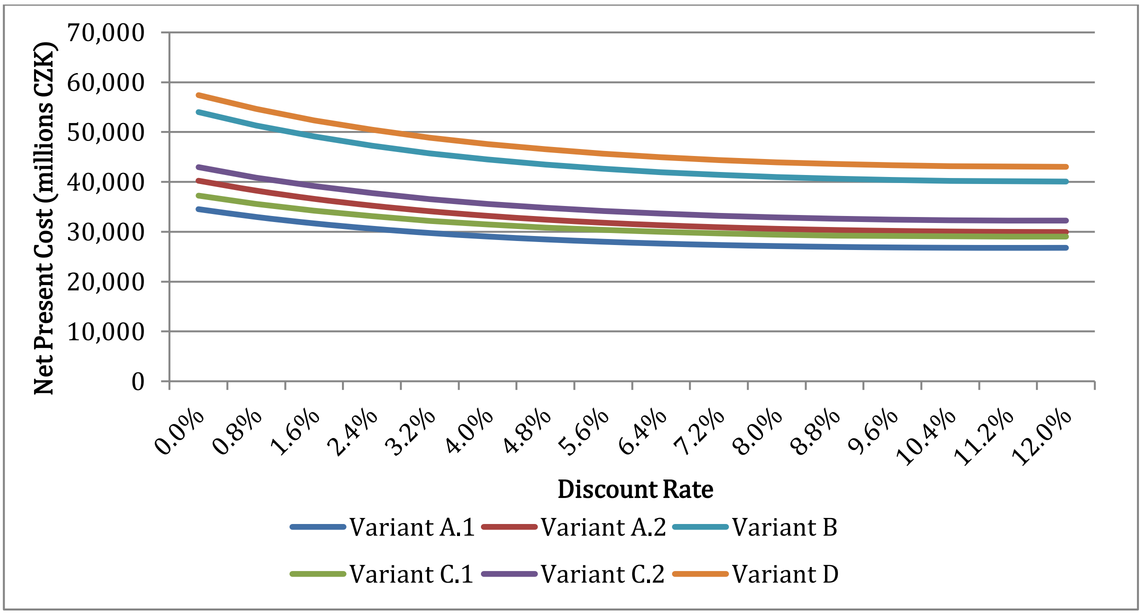


FIGURE 24: DEPENDENCE OF NPC ON DISCOUNT RATE.

Then, a sensitivity analysis was performed on NPC to changes in the investment cost of the converter stations and transmission lines, resulting in Figure 25. As shown, it reflects the high impact of this variable on the value obtained in all variants.

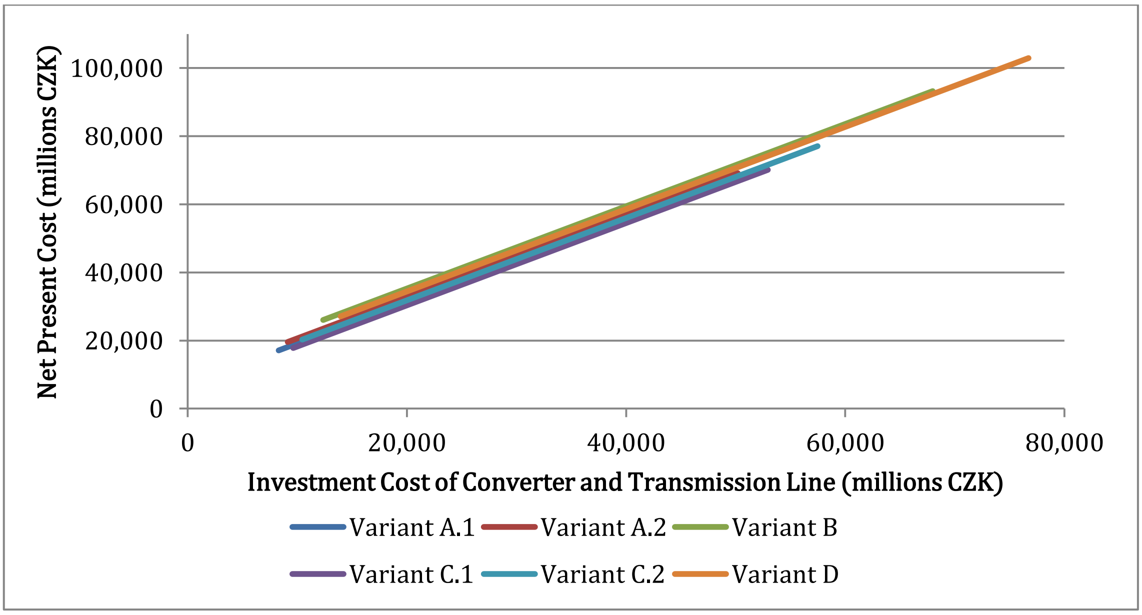
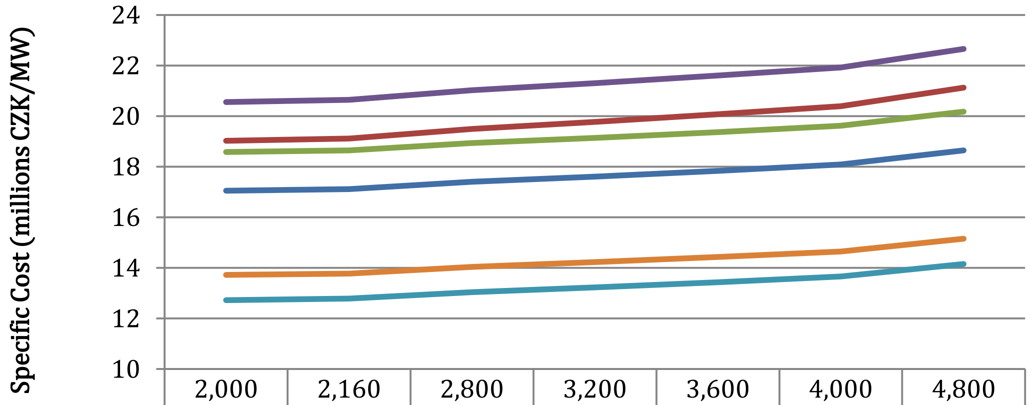


FIGURE 25: DEPENDENCE OF NPC ON INVESTMENT COST OF THE CONVERTER STATIONS AND TRANSMISSION LINE

In Figure 26, the dependence between the specific cost (CZK/MW) of each of the variants, with respect to the time of use is shown. It is appreciated that variant B has the lowest cost among all the options and with a considerable difference. It is also evident that variants using VSC technology (i.e. A.2 and C.2) have the highest costs and the difference is very marked compared to the other variants.



	2,000	2,160	2,800	3,200	3,600	4,000	4,800
Variant A.1	17.05	17.11	17.40	17.61	17.83	18.08	18.64
Variant A.2	19.03	19.11	19.49	19.77	20.07	20.39	21.13
Variant B	12.73	12.78	13.04	13.23	13.43	13.65	14.15
Variant C.1	18.58	18.64	18.93	19.14	19.37	19.61	20.17
Variant C.2	20.56	20.64	21.03	21.30	21.60	21.93	22.66
Variant D	13.72	13.78	14.04	14.22	14.43	14.65	15.15

Time of Usage Tm (h/year)

FIGURE 26: DEPENDENCE OF SPECIFIC COST (CZK/MW) OF VARIANTS ON TIME USAGE.

4.5.2. Optimal Transmission Power of Variants

To find the optimal transmission power, the net present cost must be minimized. This is done from the equation (38) previously used; it can be rewritten as follows:

$$NPC = N_i + \frac{O\&MCost}{a(r,T)} + \frac{Cost\ of\ Losses}{a(r,T)}$$

Where,

- $N_i = \sum_{t=-7}^{0} \frac{Inv_t}{(1+r)^t}$
- $O\&MCost = O\&MConverter\ Station + O\&M\ Transmission\ Line$
- $Cost\ of\ Losses =$
  $\left\{2[\text{No load losses in } \% + \text{Load losses in } \%\,]P_m + \frac{R_{DC\ per\ pole} * L * P_m{}^2}{2 * V^2}\right\} * LRMC$

Then, the following expression is minimized and derived by Pm annulated, where Pm is the unknown: optimal transmission power.

$$\frac{N_i * a(r,T)}{P_m} + \frac{O\&MCost}{P_m} + \frac{R_{DC\ per\ pole} * L * LRMC * P_m}{2V^2}$$

$$\frac{N_i * a(r,T)}{P_m{}^2} + \frac{O\&MCosts}{P_m{}^2} + \frac{R_{DC\ per\ pole} * L * LRMC}{2V^2} = 0$$

Finally, the optimum transmission power can be calculated from equation (39):

$$P_m = \sqrt{\frac{2 * V^2[N_i * a(r,T) + O\&MCost]}{R_{DC\ per\ pole} * L * LRMC}} \qquad (39)$$

Where:

V = Sending end voltage, pole to ground.
$a(r,T)$= Annuity factor.
Ni = Cumulative investment cost.
$O\&MCost$ = Operating and maintenance cost of stations and transmission line.

$R_{DCper\ pole}$ = DC resistance of the pole.
L = Distance.
LRMC = Long Run Marginal Cost of Electricity.

TABLE 22: PARAMETERS AND RESULTS FOR THE OPTIMAL TRANSMISSION POWER.

Variant	A.1	A.2	B	C.1	C.2	D
Voltage Rated [kV]	± 400	± 400	± 500	± 400	± 400	± 500
Power Rated [MW]	1,5000	1,5000	3,000	1,500	1,500	3,000
Ni [million CZK]	21,253.17	23,246.23	31,077.47	23,252.38	25,245.44	33,700.85
O&M [million CZK]	136.00	144.25	187.20	162.50	170.75	219.00
R_{DC} [Ω/km]	0.017715	0.017715	0.011810	0.017715	0.017715	0.011810
LRMC [CZK/MW]	4.13					
a(8%, 30y)	0.088827					
L[km]	530					
P_m [MW]	4,086	4,269	7,550	4,287	4,462	7,882

As can be seen from the results attained in Table 22, for all variants the optimum transmission power is up to 3 times more than the rated power, which means that it would be good to increase the transmission capacity of the link, this would be achieved by adding more conductors to the bundle in the variants, to achieve the increase in the cross section. But the increase in the number of conductors would be limited to the support of the structure and evidently how much would increase the net present cost of the variants to handle this increase in the power capacity.

Then, the net present cost and the specific cost (CZK/MW) of each of the variants were plotted according to the transmitted power, and are presented in Figure 27 and 28.

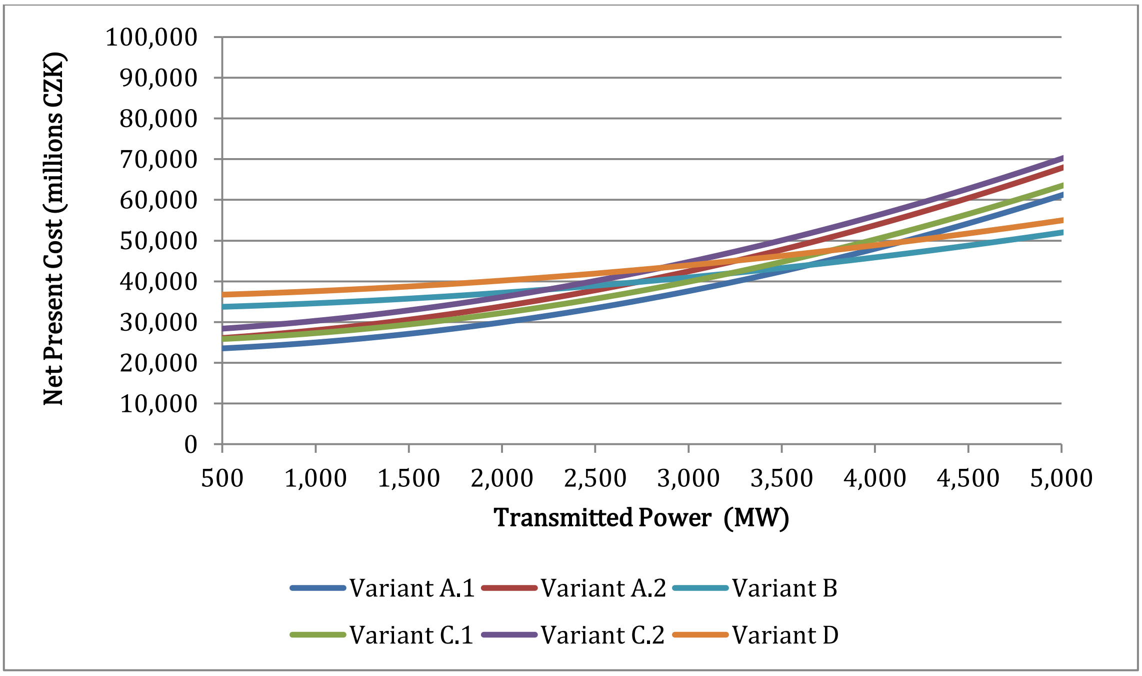


FIGURE 27: DEPENDENCE OF NET PRESENT COST ON TRANSMITTED POWER.

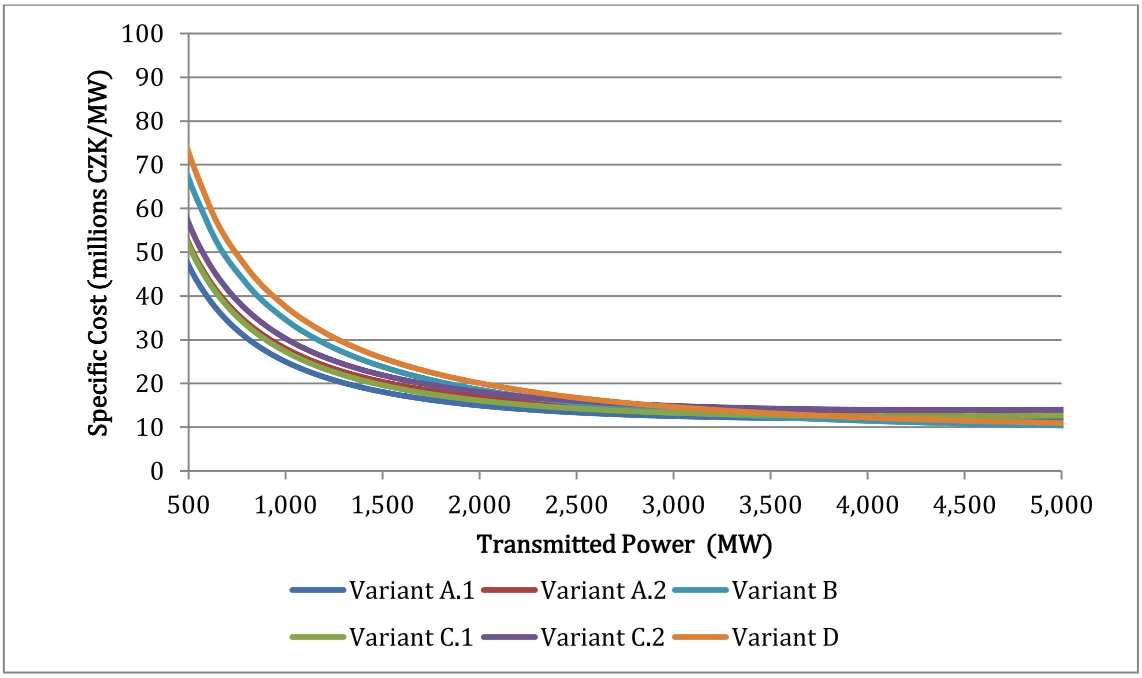


FIGURE 28: DEPENDENCE OF SPECIFIC COST ON TRANSMITTED POWER.

4.5.3. PRICE OF TRANSPORT ENERGY

In this section, the price of transport energy through the link was calculated at different rates of return, i.e. IRR = 6%, 8% or 12%. Generally, the price should be composed of three variables power (MW), energy (MWh) and distance (km), but looking for the simplification of the analysis it was decided to look only at the price of energy transported (C_E). This was obtained by equalizing to zero the equation 38 and adding the component of energy transported, being as follows:

$$NPV = -\sum_{t=-7}^{0} \frac{Inv_t}{(1+IRR)^t} - \frac{O\&MCost}{a(IRR,T)} - \frac{Cost\ of\ Losses}{a(IRR,T)} + \frac{P * T_m * C_E}{a(IRR,T)} = 0$$

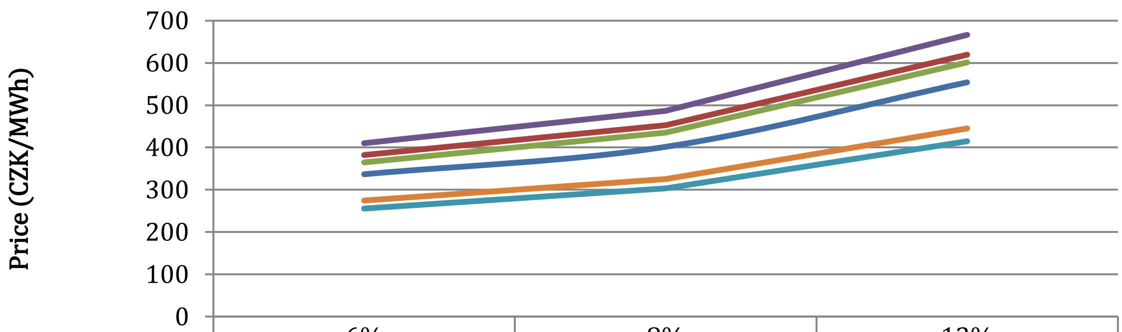
Where:

t = Time of the flow.
IRR = Internal rate of return.
Inv_t= Investment cost at time t.
$Cost\ of\ Losses$ = Cost of energy losses.
$O\&MCost$ = Operating and maintenance cost of stations and transmission line.

P = Power transmitted.
Tm = Time of usage.
C_E = Price of energy transported.
$a(r,T)$= annuity factor.

TABLE 23: PARAMETERS FOR CALCULATIONS OF PRICE.

Variant	A.1	A.2	B	C.1	C.2	D
P [MW]	1,5000	1,5000	3,000	1,500	1,500	3,000
O&M [million CZK]	136.00	144.25	187.20	162.50	170.75	219.00
Cost of losses [million CZK/year]	385.49	508.18	690.98	385.49	508.18	690.98
Tm[h/year]	4000					
$a(6\%, 30y)$	0.072649					
$a(8\%, 30y)$	0.088827					
$a(12\%, 30y)$	0.124144					



Rate of return	6%	8%	12%
Variant A.1	336.68	401.56	554.07
Variant A.2	381.96	452.89	619.57
Variant B	255.88	303.23	414.41
Variant C.1	365.01	435.57	600.90
Variant C.2	410.30	486.90	666.40
Variant D	274.16	325.30	445.10

FIGURE 29: RESULTS FOR PRICE.

From the results obtained in Figure 29, for the applied rates and assuming a transport of energy for 4000 h/year, it is observed that the lowest price for a rate of return of 6% would be given by variant B with 255.88 CZK/MWh and the greater would be the variant C.2 with 410.30 CZK/MWh. On the other hand, at the rate of 12%, both variants were again obtained representing the lowest and highest prices, i.e. 414.41 CZK/MWh and 666.40 CZK/MWh, respectively. It should be noted that for the base case, when the rate is 8 %, all variants have values above 300 CZK/MWh, being variant B the lowest with a value of 303.23 CZK/MWh.

4.6. German Proposals

The cost of connecting wind farms located in northern Germany with the major consumption centers in the south has increased due to the complex scenario among the population; the priority was given to the use of underground HVDC cable, which has produced an increase in investment cost, previously presented in Table 3, Section 2.2.

In this sense, Tennet TSO GmbH, one of the operators of the network that builds the Südlinks (Corridor A), estimates that the total cost will amount to 10 billion euros from the estimated 3 billion euros initially; additional, the work will be delayed until 2025 [50, 60, 84]. Investments cost will be higher because overhead lines were initially planned. While another of the projects, Südostlink (Corridor D), has also been postponed to 2025 and it has been indicated that it cost will also increase in the same proportion of the 1 billion euros [50, 60]. These delays are due to the decision to put some high voltage lines underground after protests by local residents. These changes represent consequences for the planning, financing, and design of the projects.

However, in making a comparison with the estimated investment cost for an HVDC link through the Czech Republic, the amounts do not deviate so much from the initial estimates in the development plans of the German network; but because of the changes of technologies to be used, i.e. underground cable instead of overhead lines, the variants cannot be directly compared. Because as was explained in Section 4.5.1 a comparison only on the investment cost is not always the best criteria for making a choice among alternatives, and other criteria must be taken into account to make a decision. On the other hand, among the causes of the investment cost of the German lines to be higher in comparison to one through the Czech Republic could be due to:

- The difference in the general price level that is higher in Germany than in the Czech Republic.
- It will give priority to the underground cable, and this usually carries costs higher than the use of OHL.
- The development of any new corridor required for German lines entails costs associated with rights of land, which can be quite complicated to anticipate and in many cases implied high costs.

CONCLUSION

Through the progress of this work aimed to provide information about HVDC transmission technology and to suggest a case study to implement an HVDC link. During the first part, an overview of the technology, the requirements, advantages, and disadvantages of the same was realized. This, to be able to implement this knowledge to the application of a simulated case study concerning the costs and factors that would influence it.

Then, I analyzed a simulated case study, where it was necessary to design variants for a link using HVDC technology. In the first stage, I required to quantify the needs, which resulted in the estimation of the link distance; the selection of the route and the space; the quantification and sketch for support structures; the selection of the arrangement of conductors and their capacity; as well as the technology to be applied in the converter stations. Obtaining a set of variants with adjusted characteristics, which were evaluated from an economic point of view in the second stage of the analysis. The economic analysis sought to compare the variants through different calculations such as the net present cost, specific costs, and optimal transmission power.

From these analyses, it is reflected that:

- At a greater distance, HVDC technology offers significant advantages over an HVAC system such as lower losses, less space required, and higher transport capacity.

- In the comparison of the designs of the proposed support structures, the size of the pylons for the HVDC variants with the same level of power transmission is lower than an AC. This feature of HVDC systems caused a decrease in the size of the corridor and right of way; that result in the reduction of the visual impacts; saving lands compensation and make possible the increase of the power transmission capacity for the existing right of way.

- By calculating the net present cost, among all the variants the one that had the best performance was the variant B, which proposed a corridor parallel to the existing one, with a capacity of 3,000MW at $\pm$ 500kV using LCC technology.

- From the calculation of the optimal power of transmission, I suggested that it is better to increase the proposed capacity of the link. This is achieved through the addition of conductors in the pole arrangements to increase the overall cross-section. Also, I mentioned that this increase is restricted by the support capacity of the structures, and clearly to the increase of the total cost of the variant by that adequacy.

- Regarding the calculation of the cost of transport of energy, its simplification was in the lack of some necessary data and the complication of the exercise. Therefore, some assumptions were made for the transport of energy given the conditions, which may vary from a realistic case, since it would be better if this price had three components: power capacity, energy, and distance.

- From my point of view, one way to increase the flexibility of the link is to propose a third converter station in the Czech Republic to create a multi-terminal topology. Although a recommendation like this would impact the total cost of the proposal, since HVDC converter stations have a significant impact on the total cost of the project; on the other hand, this could increase the flexibility of the link, since the proposed link is a point-to-point configuration between the substations in Germany and Austria. By creating this multi-terminal topology, it can be expected that not only would there be exchanges of energy between these two countries, but that the Czech Republic could also function as an energy seller in cases where both Germany and Austria needed it.

- Also through the analysis, made to the variants it was demonstrated how dependent it is on the investment costs, as well as the time of use. These variables clearly impact on the capacity of the link and it has been shown that a link with greater capacity is necessary but this also means that the link could has less annual usage time, which results in a problem of effectiveness.

Finally, one of the biggest limitations of this study was the difficulty in obtaining data to perform the analysis against the German proposals. The changes that have been made in the initial German proposals changes the perspectives and therefore the comparison could not be direct, as has been explained. Therefore, among the recommendations for the improvement of this analysis could be the presentation of other variants including underground links; the analysis of a multi-terminal link, rather than a point-to-point configuration; and an in-depth analysis of the benefits that would represent a link of this nature for the region's transmission network.

REFERENCES

BOOKS

[1]. ADAIR, G. *Thomas Alva Edison: Inventing the Electric Age*. United States of America: Oxford University Press, 1996.

[2]. ARRILLAGA, J., LIU, Y.H., WATSON, N.R. *Flexible power transmission—the HVDC Options*. John Wiley & Sons, Ltd., 2007.

[3]. BREALY, R, MYERS, S., MARCUS, A. *Fundamentals of Corporate Finance Third Edition.* Third Edition. McGraw-Hill, 2001.

[4]. CHAN-KI K., et al. *HVDC Transmission: Power Conversion Applications in Power Systems*. John Wiley & Sons Pte. Ltd., 2009.

[5]. FENCL, F. *Rozvodná Zařízení*. České Vysoké Učení Technické v Praze. Elektrotechnická Fakulta. Praha: ČVUT, 2000.

[6]. GRIGSBY, L. *Electric Power Generation, Transmission, and Distribution*. PRC Press, 2007.

[7]. JOVCIC, D., AHMED, K. *High Voltage Direct Current Transmission: Converters, Systems and DC Grids*. John Wiley & Sons, Ltd, 2015.

[8]. PADIYAR, K. HVDC *Power Transmission Systems: Technology and System Interactions*. New Delhi: New Age International (P) Limited, Publishers, 2015.

[9]. SALVATORE, D. *Managerial Economics in a Global Economy.* Oxford University Press, 2007

[10]. VAN HERTEM, D., GOMIS-BELLMUNT, O., LIANG, J. *HVDC Grids: For Offshore and Supergrid of the Future*. John Wiley & Sons, 2016.

THESES

[11]. ASSEFA, A. *Study on Conversion of Existing HVAC Lines to Hybrid HVAC/HVDC Transmission Line to Increase Transmission Capacity and Efficiency. Case of GIBE III – Addis Ababa 400KV line*. Master Thesis. Addis Ababa University, 2015.

[12]. KILONZI, C. *Design of High Voltage Direct Current (HVDC) Line from Ethiopia to Isinya (Kenya)*. University of Nairobi, 2011.

[13]. NOVOA, J. Metodología Para El Planeamiento del Sistema de Transmisión Integrado con la Conversión de Líneas de HVAC A HVDC. Universidad de los Andes, 2015.

[14]. PARDO, S. *Programa informático para el cálculo mecánico de conductores y cálculo de tablas de tendido de líneas aéreas de energía eléctrica y su aplicación para el diseño de líneas aéreas*. Universidad Carlos III de Madrid, 2010.

[15]. VIDAL, M. *Análisis Comparativo de Tecnologías de Transporte en Alta Tensión*. Universidad de Sevilla, 2014.

[16]. WORKU, E. *Study to Upgrade Existing HVAC Transmission Line to HVDC: Case of EPP's HV Transmission Lines*. Master Thesis. Addis Ababa University, 2015.

PROCEEDINGS OF CONFERENCES

[17]. JONSSON, T., BJÖRKLUND, P-E. *Capacitor Commutated Converters for HVDC*. IEEE Power Tech. Conference, Stockholm, 1995.

[18]. KOSHCHEEV, L. Environmental Characteristics of HVDC Overhead Transmission Lines. High Voltage Direct Current Power Transmission. Third Workshop on Power Grid Interconnection in Northeast Asia, Vladivostok, Russia, September 30 - October 3, 2003.

[19]. RUDERVALL, R. et al. *High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper*. Energy Week 2000, Washington, D.C, USA, March 7-8, 2000.

[20]. SINGH, A., BRITTEN, C., STEPHEN, R., MUFTIC, D. *Optimized Conductor and Conductor Bundle Solutions for Long Distance HVDC Transmission*". Inaugural IEEE PES 2005 Conference and Exposition in Africa Durban, South Africa, 11-15 July 2005.

[21]. VITEK, M. *Effects of German Nuclear Power Plants Closure on Future Electricity Cost in Central Europe*. ICONE20-POWER2012, Anaheim, California, USA, July 30-August 3, 2012.

ARTICLES IN MAGAZINES

[22]. ANDERSSON, G., FRANCK, C. *Guest Editorial Special Section on HVDC Systems and Technologies.* IEEE Transactions on Power Delivery, Volume: 29, Issue: 1, February 2014.

[23]. BAHRMAN, M., JOHNSON, B. *The ABCs of HVDC Transmission Technologies*. IEEE Power & Energy Magazine, Volume: 5, Issue: 2, March-April 2007.

[24]. BEHRAVESH, V., ABBASPOUR, N. *New Comparison of HVDC and HVAC Transmission system*. International Journal of Engineering Innovation & Research, Volume: 1, Issue: 3.

[25]. BHAR, C., ARIHAR, S. A study on risk factors involved in electrical transmission line projects: A comparative study of ISM (Interpretative Structural Modelling) and AHP (Analytical Hierarchy Process) method. NMIMS Management Review, Volume XXVI, January-February 2015.

[26]. DHANANJAY, N. et al. VSC-HVDC System for Performance Enhancement. International Journal of Engineering Research & Technology (IJERT), Volume: 2, Issue: 10, October 2013.

[27]. PAT NAIDOO. *Upgrading existing transmission lines from HVAC to HVDC*. Energize: The independent power and energy journal of Southern Africa. November 2011.

[28]. VAN HERTEM, D., GHANDHARIA, M. *Multi-terminal VSC HVDC for the European Supergrid: Obstacles*. Renewable and Sustainable Energy Reviews, Volume: 14, 2010.

[29]. WILLIS, L., NILSSON, S. *HVDC Transmission: Yesterday and Today*. IEEE Power & Energy Magazine, Volume: 5, Issue: 2, March-April 2007.

WWW RESOURCES

[30]. The early HVDC development: The key challenge in the HVDC technique. ABB Power Technologies AB. [online] [accessed 22.10.2016] Available on: https://library.e.abb.com/public/93e7f5ea0e800b7cc1257ac3003f4955/HVDC_50years.pdf

[31]. Uno Lamm and the dawn of HVDC. [online] [accessed 22.10.2016] Available on: http://www.abb.com/cawp/seitp202/5704f0f72bf85ee8c1257cba00482cf5.aspx

[32]. HVDC veterans' presentations: The history of HVDC Part 1: The mercury arc valve era and the history of HVDC Part 2: ASEA's HVDC Thyristor Introduction 1965 – 1980. ABB Power Technologies AB. [online] [accessed 23.10.2016] Available on: https://library.e.abb.com/public/c637018c8f3bc65cc12574f700642dd0/HVDC%20veterans.pdf

[33]. ABB HVDC Reference Projects: Konti-Skan. ABB. [online] [accessed 23.10.2016] Available on: http://new.abb.com/systems/hvdc/references/konti-skan

[34]. ABB HVDC Reference Projects: New Zealand. ABB. [online] [accessed 23.10.2016] Available on: http://new.abb.com/systems/hvdc/references/new-zealand
[35]. ABB HVDC Reference Projects: SAPEI. ABB. [online] [accessed 23.10.2016] Available http://new.abb.com/systems/hvdc/references/sapei
[36]. ABB HVDC Reference Projects: Pacific Intertie. ABB. [online] [accessed 23.10.2016] Available on: http://new.abb.com/systems/hvdc/references/pacific-intertie
[37]. ABB HVDC Reference Projects: Eel River. ABB. [online] [accessed 24.10.2016] Available on: http://new.abb.com/systems/hvdc/references/eel-river
[38]. Milestones: Nelson River HVDC Transmission System, 1972. IEEE Winnipeg Section, Dedication: 3 June 2005. [online] [accessed 24.10.2016] Available on: http://ethw.org/Milestones:Nelson_River_HVDC_Transmission_System,_1972
[39]. ABB HVDC Reference Projects: Itaipu. ABB. [online] [accessed 24.10.2016] Available on: http://new.abb.com/systems/hvdc/references/itaipu
[40]. An Electrifying History Powering Today's Advancements. [online] [accessed 24.10.2016] Available on: http://lec.alterisgroup.net/index.php/hvdc-technology
[41]. Economic and environmental advantages. ABB. [online] [accessed 8.10.2016] Available on: http://new.abb.com/systems/hvdc/why-hvdc/economic-and-environmental-advantages
[42]. Technical advantages. ABB. [online] [accessed 8.10.2016] Available on: http://new.abb.com/systems/hvdc/why-hvdc/technical-advantages
[43]. Renewable electricity futures study. Volume 4: bulk electric power systems: operations and transmission planning. National Renewable Energy Laboratory (NREL). [online][accessed 16.10.2016] Available on: http://www.nrel.gov/docs/fy12osti/52409-4.pdf
[44]. MUKHEDKAR, R. Introduction to HVDC. ALSTOM. [online] [accessed 7.11.2016] Available on: http://sari-energy.org/oldsite/PageFiles/What_We_Do/activities/HVDC_Training/Presentations/Day_7/LCC_vs_VSC_ALSTOM.pdf
[45]. Marx, B., Gräßler, B., Bolívar, L. El Gobierno alemán aprueba el apagón nuclear para 2022. [online][accessed 28.11.2016] Available on: http://dw.com/p/11Qvk
[46]. Energy Charts: Annual electricity generation in Germany. Fraunhofer ISE. [online][accessed 13.12.2016] Available on: https://www.energy-charts.de/energy.htm
[47]. Netzentwicklungsplan Strom. [online] [accessed 6.12.2016] Available on: https://www.netzentwicklungsplan.de/en/
[48]. Amprion GmbH. [online] [accessed 6.12.2016] Available on: http://amprion.net/de/
[49]. TransnetBW GmbH. [online] [accessed 6.12.2016] Available on: https://www.transnetbw.de/de
[50]. TenneT TSO GmbH. [online][accessed 6.12.2016] Available on: http://www.tennet.eu/de/
[51]. 50Hertz Transmission GmbH. [online] [accessed 6.12.2016] Available on: http://www.50hertz.com/de/
[52]. Making a success of the energy transition: On the road to a secure, clean and affordable energy supply. Federal Ministry for Economic Affairs and Energy. 2015. [online] [accessed 13.12.2016] Available on: http://www.bmwi.de/EN/Service/publications,did=721520.html

[53]. How it works: Grid expansion in five steps [online] [accessed 18.01.2017] Available online on: https://www.netzausbau.de/EN/5steps/en.html
[54]. AMELANG, S., APPUNN, K., WETTENGEL, J. Delay in power grid extension / 'E.ON about to restart'. Published on 07.06.2016. [online] [accessed 18.01.2017] Available online on: https://www.cleanenergywire.org/news/delay-power-grid-extension-eon-about-restart
[55]. European Network of Transmission System Operators for Electricity. [online] [accessed 20.01.2016] Available on: https://www.entsoe.eu
[56]. What is Sag, Tension? Calculations, Factors in Overhead Transmission Lines. [online] [accessed 25.02.2017] Available online on: http://www.electricaledition.com/2016/02/sag-tension-in-electrical-transmission.html
[57]. PROCHÁZKA, R. Venkovní vedení VVN. In TZB-INFO 28/5/2007. [online] [accessed 02.03.2017] Available on: http://www.tzb-info.cz/4151-venkovni-vedeni-vvn-ii
[58]. Česká Přenosová Soustava. ČEPS, a.s [online] [accessed 03.03.2017] Available on: http://www.ceps.cz/ENG/Pages/default.aspx
[59]. Czech National Bank. Central bank exchange rates fixing - [online] [accessed 04.04.2017] Available on: https://www.cnb.cz/en/financial_markets/foreign_exchange_market
[60]. Zhan, W., Parkin, B. Germany to Build $11 Billion Power Link as Cost Estimate Doubles. [online] [accessed 18.05.2017] Available on: https://www.bloomberg.com/news/articles/2016-06-09/germany-to-build-11-billion-power-link-as-cost-estimate-doubles

Other Resources

[61]. HVDC for Beginners and Beyond. ALSTOM Grid, Systems-L4-HVDC Basics-2165-V2-EN.
[62]. High Voltage Direct Current Transmission – Proven Technology for Power Exchange. Siemens AG-Power Transmission and Distribution: High Voltage Division, Erlangen, Germany, 2011.
[63]. WEIMERS, L. Bulk Power Transmission at Extra High Voltages, a Comparison between Transmission Lines for HVDC at Voltage above 600 kV DC and 800 kV AC. ABB Power Technologies AB.
[64]. HVDC Light. It´s time to connect. ABB AB Grid Systems – HVDC. 2013 ABB Id No: POW-0038. Rev. 7.
[65]. Typical Technical Specification for an HVDC Light Link Transmission Project. . ABB 1JNL100098-754 Rev.00.
[66]. SANDERS, M., RAY, R. Power Line Carrier Channel & Application Considerations For Transmission Line Relaying. Pulsar Technologies, Inc. Pulsar Document Number C045–P0597
[67]. MORRIS, C., PEHNT, M. Energy Transition. The German Energiewende. Heinrich Böll Stiftung. Germany, 2016.
[68]. CIGRE. HVDC Environmental Planning Guidelines. Working Group B4.44. October 2012.
[69]. CIGRE. Impacts of HVDC Lines on the Economics of HVDC Projects, JWGB2/B4/C1.17, June 2008.
[70]. HATCH, "DC1010-Voltage and Conductor Optimization" The Lower Churchill Project, April 2008.

[71]. CIGRE. Thermal Behavior of Overhead Conductors. Study Committee 22 Working Group 12. September 2001.
[72]. IEC 60071-2. Insulation Coordination – Part 2: Application guide. Reference number IEC 60071-2:1996(E).
[73]. RETZMANN, D. HVDC Station Layout, Equipment LCC & VSC and Integration of Renewables using HVDC. CIGRE Tutorial 2012.
[74]. CIGRE. Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies, Working Group B4.46, April 2012.
[75]. CIGRE. HVDC Grid Feasibility. Working Group B4.52, April 2013.
[76]. European Commission. e-HIGHWAYS 2050. Modular Development Plan of the Plan-European Transmission System 2050. 2014.
[77]. Stantec. Alberta energy. 2009. Assessment and Analysis of the State-Of-the-Art Electric Transmission Systems with Specific Focus on High-Voltage Direct Current (HVDC), Underground or Other New or Developing Technologies. December 23, 2009.
[78]. Peterová, Barbora: media spokesperson ČEPS, a.s. Consultation. [Email]. 2017.
[79]. CIGRE. Impacts of HVDC Lines on the Economics of HVDC Projects, Joint Working Group B2/B4/C1.17, August 2009.
[80]. VITEK, M. *Dlouhodobé marginální náklady na elektøinu metodou reprezentantu.* Praha: ČVUT.
[81]. European Commission. Study on regulatory incentives for investments in electricity and gas infrastructure projects - Final Report. 2014.
[82]. Energetický regulační úřad: Zpráva Energetického regulačního úřadu o metodice regulace IV. regulačního období pro odvětví elektroenergetiky a plynárenství.
[83]. ELAND Cables Catalog.
[84]. ENTSO-E. TYNP 2016: Project Sheets.
[85]. EGE-ENERGOVOD: Geometrie Stožárových Konstrukcí 220 A 400 KV.

APPENDICES

Annex A: Maps

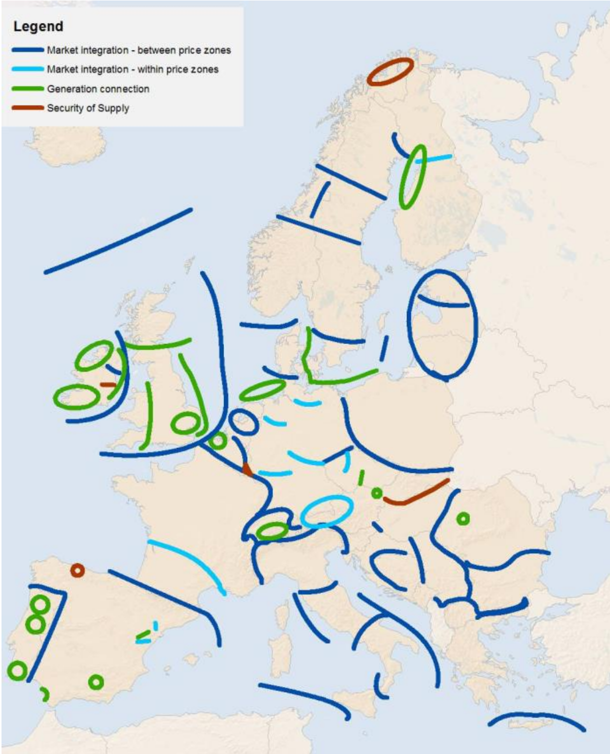


FIGURE A.1: MAP OF MAIN BOTTLENECKS IN THE ENTSO-E PERIMETER TYNP 2014 [55].

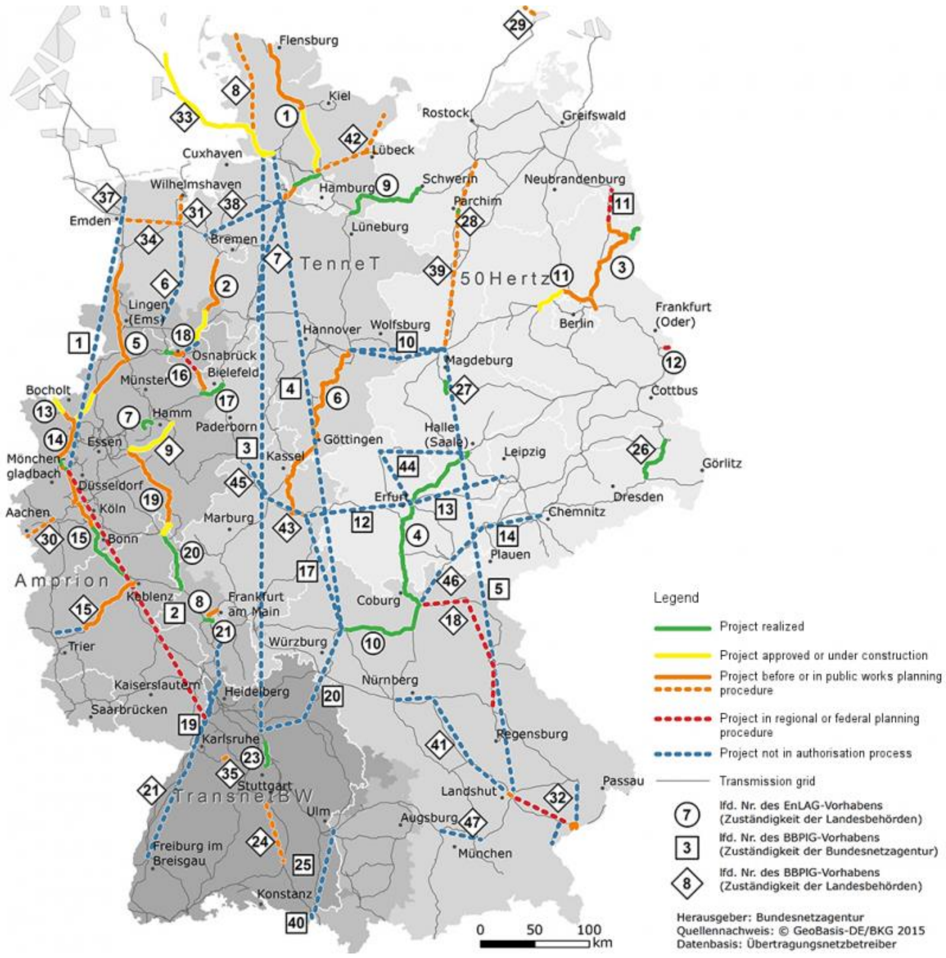


FIGURE A.2: GRID EXPANSION PLANNED ACCORDING TO THE BUNDESBEDARFSPLANGESETZ [54].

ANNEX B: ENVIRONMENTAL CONSIDERATIONS

TABLE B.1: ENVIRONMENTAL ISSUES OF HVDC OVERHEAD LINE TRANSMISSION [68].

Issues	Environmental Impact	Mitigation
Corona Effects	Audible noise and radio interference.	Proper design.
Conductor Surface Gradient	Visual Impacts and others like noise.	Proper conductor bundle design.
Electromagnetic Interference	Sound and image noise.	Appropriate ROW width; proper conductor bundle design; installation of dedicated antenna at homes.
Audible Noise	Noise.	Appropriate ROW width; proper conductor bundle design; installation of sound barrier or dynamic noise cancellation.
Electric Fields and Ions	Perceived effect on skin and hair.	Appropriate conductor to ground height; appropriate bundle design.
Magnetic Field	Compass deviation and possible effect on animal and bird orientation.	Appropriate conductor to ground height; avoid critical areas.
Harmonics on the DC side	Telephone interference; coupling into adjacent AC lines.	Appropriate DC filters design; change or relocation of telephone circuits.
Visual	Aesthetic; Birds collisions.	Route selection; tower appearance; birds' diverters.
Woodland	Tree removal; effect on habitat, flora and fauna.	Route selection; adjusting tower placement and span length to minimize the need for tree removal; follow guidelines for preventing the spread of invasive plant species and diseases.
Cultural Heritage	Damage to components of heritage.	Route selection.

TABLE B.2: ENVIRONMENTAL ISSUES OF HVDC CONVERTER STATION [68]

Equipment	Environmental Impact	Mitigation
AC Filters	Visual; audible noise; oil filled capacitors.	Enclosure / housing; sound barriers, low noise design; oil containment.
Converter Transformers	Visual; audible noise; oil.	Enclosure / housing; sound barriers, low noise design; oil containment, plus oil separators.
Thyristors Valves	Audible noise; radio interference; valve halls are large/tall: visual impact; EMF.	Building, shielded building and RI filters, distance to neighborhoods / hide halls in terrain, distance from emission source, Shielding.
IGBT Valves	Radio interference; audible noise; EMF.	Shielded building/container and RI, filters, distance from emission source.
Smoothing Reactor	Audible noise; visual impact.	Sound barrier, enclosure / housing, oil containment, plus oil separators.
DC Filters	Visual; audible noise; oil filled capacitors.	Enclosure / housing; sound barriers, low noise design; oil containment.
DC and AC ground switches	Audible noise; radio interference.	Distance from sensitive area.
AC circuit breakers	Visual impact, SF6 gas leakage, audible noise during operation, radio interference.	Visual barriers, potential gas leakage monitoring, increased separation, low noise design, distance from sensitive area.
Thyristor valve cooling	Audible noise, glycol leakage, chemical cleaners.	Sound barriers; glycol containment or avoid glycol use; dry air coolers.
Auxiliary power and station service equipment	Audible noise, oil, SF6.	Enclosures, oil containment, leakage monitoring.
Air handling systems, heating and air conditioning	Audible noise.	Low noise equipment, enclosures.
AC and DC bus and connectors	Radio Interference.	Conservative design, corona rings.

ANNEX C: LINE ROUTING

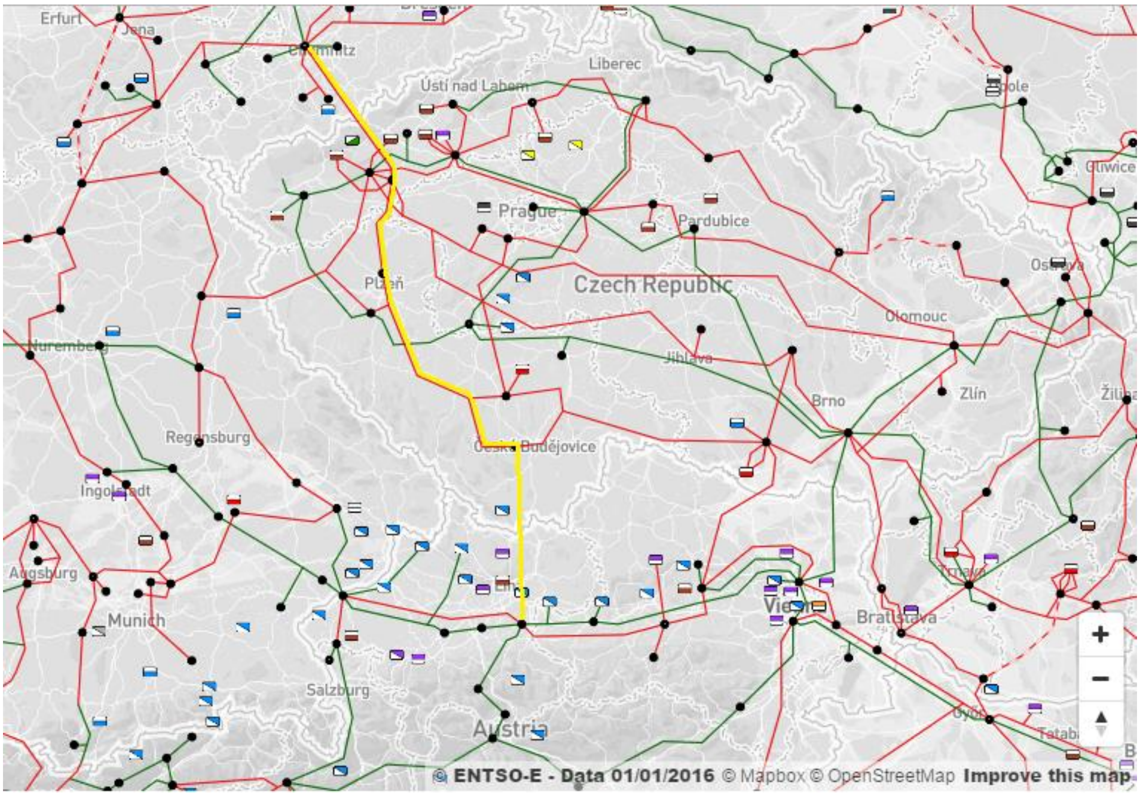


FIGURE C.1: PROPOSED ROUTE FROM RÖHRSDORF SUBSTATION TO ERNSTHOFEN SUBSTATION [55].

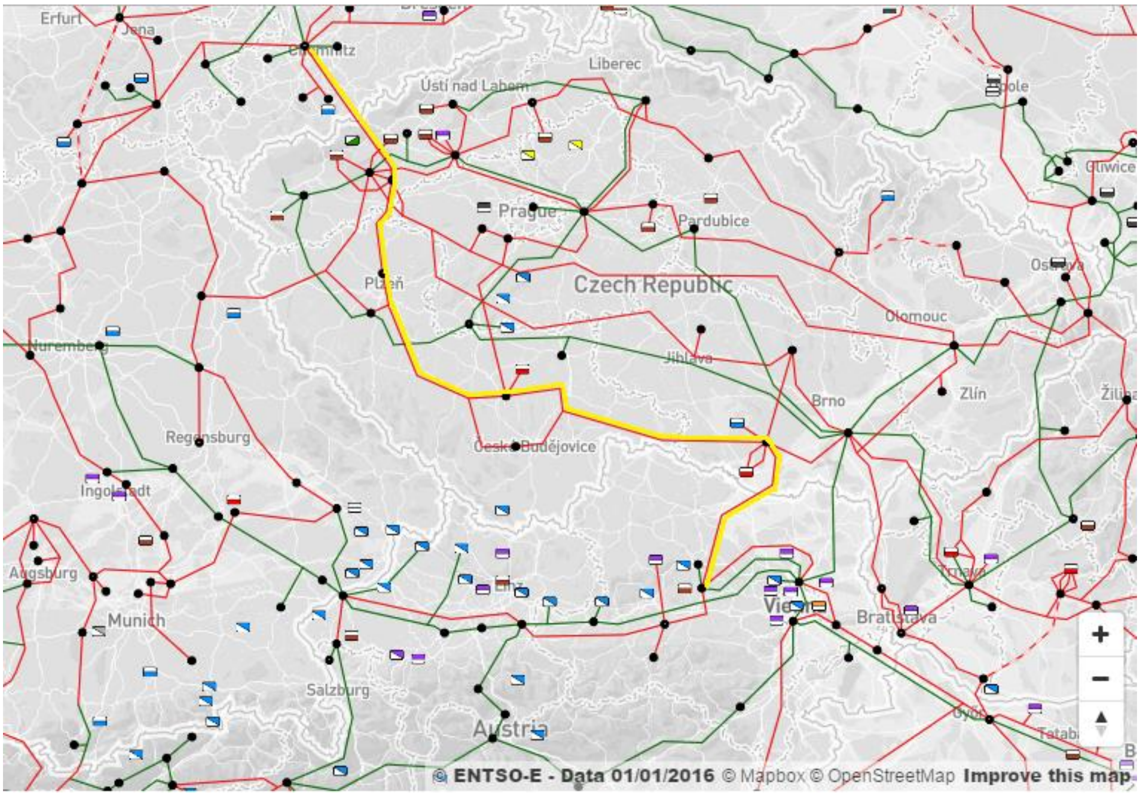


FIGURE C.2: PROPOSED ROUTE FROM RÖHRSDORF SUBSTATION TO DÜRNROHR SUBSTATION [55].

ANNEX D: HVDC SYSTEMS

Capacity (MW)	AC voltage (kV)	DC voltage (kV) (PTP)	DC voltage (kV) (BTB)
200	115	—	2 × 60
400	115–230	—	2 × 80
500	230–345	±250	2 × 100
1000	345–500	±400–500	2 × 150
1500	345–500	±500	—
2000	500	±500–600	—
2500	500	±500–600	—
3000	500	±600	—

FIGURE D.1: RELATIONSHIPS BETWEEN THE CAPACITY AND THE VOLTAGE OF HVDC SYSTEMS [4].

Nominal system voltage kV	Recommended conductor bundle order	Power transfer capability	AC technology	DC technology
132	1 x	80 MVA	100 km	
275	2 x	250 MVA	200 km	
400	2 x	350 MVA	300 km	
400	4 x	1500 MVA		400 km
765/800	6 x	5000 MVA		500 km
765/800	6 x	3500 MVA		3000 km

FIGURE D.2: RECOMMENDED POWER TRANSMISSION TECHNOLOGY FOR APPLICATION BASED ON NOMINAL SYSTEM VOLTAGE AND POWER TRANSFER [27].

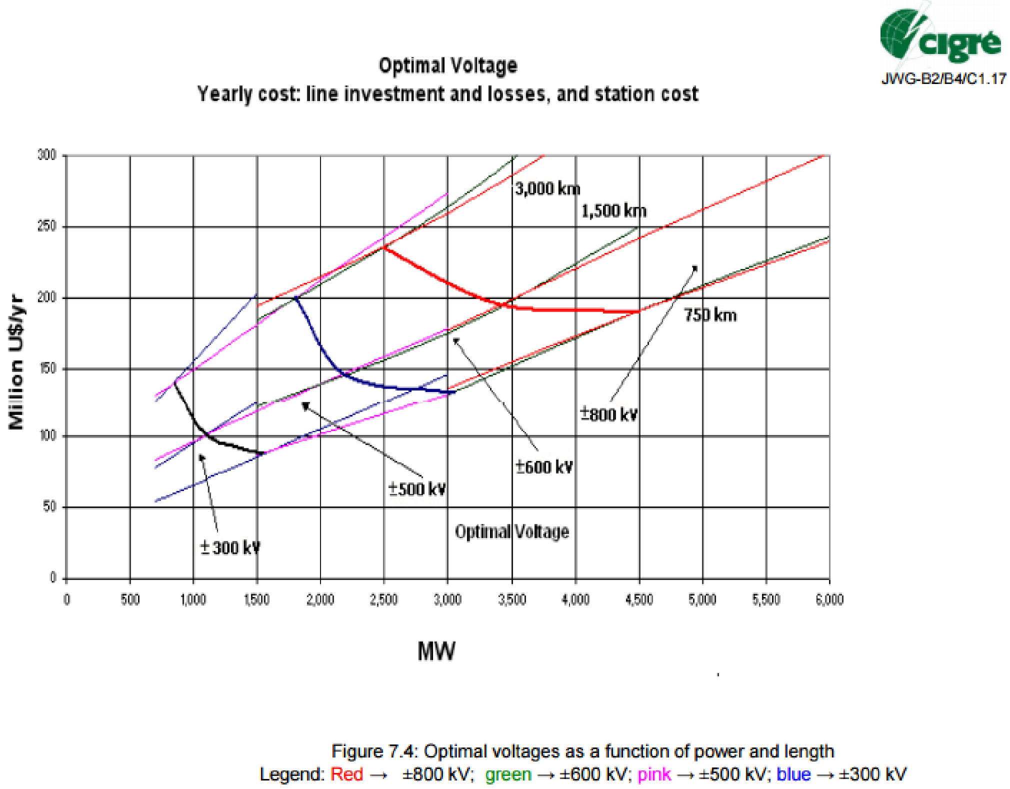


FIGURE D.3: OPTIMAL VOLTAGES AS A FUNCTION OF POWER AND LENGTH [69].

Annex E: Conductor Analysis

CODE	SIZE AWG-MCM	STRANDING No. x mm		SECTION mm²		OVERALL DIAMETER mm		CONDUCTOR WEIGHT kg/km			RATED STRENGTH kN	ELECTRICAL RESISTANCE			CURRENT CARRYING CAPACITY (1) Amps
		Al.	Steel	Total	Al.	Total	Core	Total	Al.	Steel		20°C DC	25°C AC	75°C AC	
CURLEVV	1033.5	54 x 3.52	7 x 3.52	593.6	525.5	31.68	10.56	1980.8	1451	529	162.86	0.05446	0.05677	0.06759	1150
BLUEJAY	1113	45 x 4.00	7 x 2.66	604.4	565.5	31.98	7.98	1867.7	1562.6	305.1	132.6	0.05085	0.05348	0.06365	1205
FINCH	1113	54 x 3.65	19 x 2.19	636.6	565	32.85	10.95	2129.6	1570	559.6	174	0.05085	0.05315	0.06332	1205
BUNTING	1192.5	45 x 4.14	7 x 2.76	647.7	605.8	33.12	8.28	2000.1	1674.2	325.9	142.4	0.04757	0.0502	0.05938	1255
GRACKLE	1192.5	54 x 3.77	19 x 2.27	679.7	602.8	33.97	11.35	2281.4	1681.7	599.8	186.45	0.04724	0.04954	0.05906	1260
SKYLARK	1272	36 x 4.78	1 x 4.78	664	646	33.46	4.78	1916.8	1776.9	139.9	117.48	0.04462	0.04757	0.05643	1310
BITTERN	1272	45 x 4.27	7 x 2.85	489.1	644.4	34.17	8.55	2134.1	1785.8	384.3	151.74	0.04462	0.04724	0.0561	1310
PHEASANT	1272	54 x 3.90	19 x 2.34	726.8	645.1	35.1	11.7	2423.5	1783.8	639.7	199.96	0.04429	0.04659	0.05545	1310
DIPPERF	1351.5	45 x 4.40	7 x 2.93	731.4	684.2	35.19	8.79	2266.5	1898.5	368	161.08	0.04199	0.04495	0.05282	1360
MARTIN	1351.5	54 x 4.02	19 x 2.41	772.1	685.4	36.17	12.05	2585	1906.4	678.6	206.03	0.04167	0.04396	0.05217	1365
BOBOLINK	1431	45 x 4.53	7 x 3.02	775.4	725.3	36.24	9.06	2400.4	2009.1	391.3	170.43	0.0397	0.04265	0.0502	1410
PLOVER	1431	54 x 4.14	19 x 2.48	818.7	726.9	37.24	12.4	2738.3	2019	719.3	218.48	0.03937	0.04167	0.04954	1415
NUTHATCH	1510.5	45 x 4.65	7 x 3.10	817	764.2	37.2	9.3	2532.9	2120.7	412.2	178.44	0.0374	0.04035	0.04757	1455
PARROT	1510.5	54 x 4.25	19 x 2.55	863.1	766.1	38.25	12.75	2890.1	2131.1	759	230.05	0.0374	0.04003	0.04724	1460
LAPWING	1590	45 x 4.78	7 x 3.18	863.1	807.7	38.22	9.54	2666.8	2232.3	434.5	187.78	0.03576	0.03871	0.0456	1505
FALCON	1590	54 x 4.36	19 x 2.62	908.6	806.2	39.26	13.1	3041.9	2242.7	799.2	242.51	0.03543	0.03806	0.04495	1510

FIGURE E.1: MANUFACTURER'S DATA (ELAND CABLES) EXTRACT ON SELECTED CONDUCTORS [83].

TABLE E.1: VARIANT A 1,500 MW; ±400KV.

Conductors in Bundle		2.00	3.00	4.00					2.00	3.00	4.00
R_x per bundle [Ω/km]		0.064403	0.096604	0.128805							
Max Current in each strand [A]		1172	781	586					Pole Power Capacity		
Code Name	Electrical resistance (Ω/km)	Gmax (kV/cm)			Pc [W/m]	Pr [W/m]	Ps [W/m]	I_{dc} [A]	[MW]		
Darien	0.11800	36.87	27.46	22.25	51.34	12.10	10.90	604	483	725	966
Elgin	0.10100	34.53	25.72	20.85	53.23	13.07	11.77	665	532	798	1,064
Flint	0.08920	32.61	24.31	19.70	54.94	13.98	12.58	719	575	863	1,150
Greely	0.07130	29.65	22.12	17.94	57.92	15.64	14.08	826	661	992	1,322
ASTER 288	0.11540	36.43	27.13	21.99	51.68	12.28	11.05	613	490	735	980
ASTER 366	0.09080	32.90	24.52	19.88	54.67	13.83	12.45	711	569	853	1,137
ASTER 570	0.05850	27.27	20.37	16.53	60.71	17.28	15.55	935	748	1,122	1,495
ASTER 851	0.03940	23.09	17.31	14.06	58.37	21.11	19.00	1121	897	1,345	1,793
Pelican	0.11840	38.54	28.70	23.25	50.11	11.50	10.35	595	476	714	953
Flicker	0.11780	37.77	28.13	22.79	50.67	11.77	10.60	600	480	720	960
Hawk	0.11710	36.90	27.48	22.27	51.32	12.09	10.89	606	485	727	970
Hen	0.11650	36.01	26.82	21.74	52.01	12.44	11.20	612	489	734	979
Osprey	0.10140	36.08	26.87	21.78	51.96	12.42	11.18	655	524	786	1,049
Parakeet	0.10100	34.92	26.02	21.08	52.90	12.90	11.61	663	530	795	1,060
Dove	0.10070	34.50	25.71	20.83	53.25	13.08	11.78	666	533	799	1,066
Kingbird	0.08891	34.07	25.39	20.57	53.63	13.28	11.95	711	569	854	1,138
Grosbeak	0.11214	32.62	24.32	19.71	54.93	13.97	12.58	641	513	769	1,026
Cuckoo	0.07087	30.04	22.41	18.17	57.50	15.40	13.86	826	661	991	1,321
Drake	0.07054	29.69	22.15	17.96	57.88	15.62	14.06	831	664	997	1,329
Tern	0.07119	30.69	22.89	18.56	56.83	15.02	13.52	819	655	983	1,310
Condor	0.07054	30.04	22.41	18.17	57.50	15.40	13.86	828	662	993	1,324
Mallard	0.06988	28.95	21.61	17.52	58.70	16.09	14.48	841	672	1,009	1,345
Ruddy	0.06234	29.14	21.74	17.63	58.49	15.97	14.37	888	711	1,066	1,421
Cardinal	0.05906	27.78	20.74	16.83	60.08	16.90	15.21	925	740	1,110	1,480
Bluejay	0.05085	26.64	19.91	16.15	61.51	17.77	15.99	1,009	807	1,211	1,615
Grackle	0.04724	25.33	18.95	15.38	63.28	18.87	16.99	1,063	850	1,275	1,700
Pheasant	0.04429	24.65	18.45	14.98	55.51	19.50	17.55	1,030	824	1,237	1,649
Martin	0.04167	24.05	18.01	14.63	56.57	20.09	18.09	1,073	858	1,287	1,716
Parrot	0.03740	22.97	17.22	13.99	58.61	21.25	19.13	1,153	922	1,384	1,845
Falcon	0.03543	***22.48***	16.86	13.70	67.75	21.81	19.63	1,271	***1,017***	1,525	2,034
350Al/Fe4	0.08880	30.91	23.05	18.69	56.60	14.89	13.40	732	585	878	1,171
350/59	0.08350	31.31	23.35	18.93	56.19	14.66	13.20	752	601	902	1,203
445/74	0.04600	28.40	21.20	17.20	59.34	16.46	14.82	1,042	833	1,250	1,667
450/52	0.06560	28.66	21.39	17.35	59.03	16.28	14.66	870	696	1,044	1,392
680/83	0.04330	24.26	18.16	14.75	64.87	19.89	17.90	1,124	899	1,349	1,799
750/43	0.03880	23.87	17.88	14.52	65.46	20.28	18.25	1,193	955	1,432	1,909

231-AL1/30-ST1A	0.12500	38.06	28.35	22.97	50.46	11.67	10.50	581	465	698	930
243-AL1/39-ST1A	0.11880	36.86	27.45	22.24	51.35	12.11	10.90	602	481	722	963
264-AL1/34-ST1A	0.10950	36.01	26.82	21.74	52.01	12.44	11.20	631	505	757	1,010
304-AL1/49-ST1A	0.09490	33.47	24.94	20.22	54.15	13.55	12.20	692	554	830	1,107
339-AL1/30-ST1A	0.08520	32.79	24.44	19.81	54.77	13.89	12.50	735	588	881	1,175
382-AL1/49-ST1A	0.07580	30.71	22.91	18.57	56.80	15.00	13.50	793	635	952	1,269
434-AL1/56-ST1A	0.06660	29.09	21.71	17.60	58.55	16.00	14.40	860	688	1,032	1,376
550-AL1/71-ST1A	0.05260	26.35	19.70	15.98	61.89	18.00	16.20	996	796	1,195	1,593
653-AL1/45-ST1A	0.04420	25.07	18.76	15.23	63.66	19.11	17.20	1,102	882	1,322	1,763

TABLE E.2: VARIANT B 3,000 MW; ±500KV.

Conductors in Bundle		**2.00**	**3.00**	**4.00**					**2.00**	**3.00**	**4.00**
R_x per bundle [Ω/km]		0.050314	0.075472	0.100629							
Max Current in each strand [A]		1875	1250	938					**Pole Power Capacity**		
Code Name	**Electrical resistance (Ω/km)**	**Gmax** (kV/cm)			**Pc** [W/m]	**Pr** [W/m]	**Ps** [W/m]	**I_{dc}** [A]	[MW]		
Flint	0.08920	39.73	28.97	23.18	54.94	13.98	12.58	719	719	1,079	1,438
Greely	0.07130	36.11	26.36	21.09	57.92	15.64	14.08	826	826	1,240	1,653
ASTER 366	0.09080	40.08	29.23	23.38	54.67	13.83	12.45	711	711	1,066	1,422
ASTER 570	0.05850	33.20	24.26	19.43	60.71	17.28	15.55	935	935	1,402	1,870
ASTER 851	0.03940	28.10	20.60	16.52	58.37	21.11	19.00	1,121	1,121	1,681	2,242
Peacock	0.09285	41.08	29.95	23.96	53.93	13.44	12.10	698	698	1,047	1,396
Kingbird	0.08891	41.51	30.26	24.20	53.63	13.28	11.95	711	711	1,067	1,423
Cuckoo	0.07087	36.59	26.70	21.37	57.50	15.40	13.86	826	826	1,239	1,652
Drake	0.07054	36.16	26.39	21.12	57.88	15.62	14.06	831	831	1,246	1,661
Tern	0.07119	37.38	27.27	21.82	56.83	15.02	13.52	819	819	1,228	1,638
Condor	0.07054	36.59	26.70	21.37	57.50	15.40	13.86	828	828	1,242	1,655
Mallard	0.06988	35.26	25.74	20.60	58.70	16.09	14.48	841	841	1,261	1,681
Canary	0.06234	34.69	25.33	20.28	59.23	16.40	14.76	894	894	1,341	1,788
Catbird	0.05971	35.24	25.73	20.59	58.72	16.10	14.49	909	909	1,364	1,819
Rail	0.05938	34.60	25.27	20.23	59.32	16.45	14.81	917	917	1,375	1,833
Cardinal	0.05906	33.82	24.71	19.78	60.08	16.90	15.21	925	925	1,388	1,850
Bluejay	0.05085	32.43	23.71	18.99	61.51	17.77	15.99	1,009	1,009	1,514	2,019
Grackle	0.04724	30.84	22.56	18.08	63.28	18.87	16.99	1,063	1,063	1,594	2125
Pheasant	0.04429	30.01	21.97	17.60	55.51	19.50	17.55	1,030	1,030	1,546	2,061
Falcon	***0.03543***	27.36	***20.07***	16.10	67.75	21.81	19.63	1,271	1,271	***1,907***	2,542
350Al/Fe4	0.08880	37.65	27.47	21.98	56.60	14.89	13.40	732	732	1,098	1,463
350/59	0.08350	38.14	27.83	22.26	56.19	14.66	13.20	752	752	1,128	1,504
445/74	0.04600	34.58	25.26	20.22	59.34	16.46	14.82	1,042	1,042	1,563	2,083
450/52	0.06560	34.90	25.48	20.40	59.03	16.28	14.66	870	870	1,305	1,740
680/83	0.04330	29.52	21.62	17.33	64.87	19.89	17.90	1,124	1,124	1,686	2,248
750/43	0.03880	29.05	21.28	17.06	65.46	20.28	18.25	1,193	1,193	1,790	2,386
304-AL1/49-ST1A	0.09490	40.78	29.73	23.78	54.15	13.55	12.20	692	692	1,038	1,384
339-AL1/30-ST1A	0.08520	39.94	29.13	23.30	54.77	13.89	12.50	735	735	1,102	1,469
382-AL1/49-ST1A	0.07580	37.41	27.30	21.84	56.80	15.00	13.50	793	793	1,190	1,587
434-AL1/56-ST1A	0.06660	35.42	25.86	20.70	58.55	16.00	14.40	860	860	1,290	1,720
550-AL1/71-ST1A	0.05260	32.08	23.46	18.79	61.89	18.00	16.20	996	996	1,493	1,991
653-AL1/45-ST1A	0.04420	30.52	22.33	17.89	63.66	19.11	17.20	1,102	1,102	1,653	2,204

ANNEX F: THERMAL CURRENT CALCULATIONS STEADY STATE

Group of dimensionless parameter useful to calculate convective heat transfer [71]:

Nusselt Number	$Nu = \frac{h_c D}{\lambda_f}$	Where h_c is the coefficient of convective heat transfer and λ_f is the thermal conductivity of air.
Reynolds Number	$Re = \frac{\rho_r V D}{v_f}$	Where V is the wind velocity, v_f is the kinematic viscosity and ρ_r is the relative air density.
Grashof Number	$Gr = \frac{D^3 (T_s - T_a) g}{(T_f + 273) v_f^2}$	Where T_s the conductor is surface temperature and T_a is the ambient temperature.
Prandtl Number	$Pr = \frac{c\mu}{\lambda_f}$	Where c is the specific heat capacity of air at constant pressure and μ is the dynamic viscosity of air.

The empirical equations to calculate the above parameters:

$$\rho_r = e^{(-1.16\times 10^{-4} y)}$$
$$v_f = 1.32 \times 10^{-5} + 9.5 \times 10^{-8} T_f$$
$$\lambda_f = 2.42 \times 10^{-2} + 7.2 \times 10^{-5} T_f$$
$$Pr = 0.715 - 2.5 \times 10^{-4} T_f$$
$$T_f = 0.5 * (T_S + T_a)$$

Forced Convection	$Nu = B_1 (Re)^n$	Where B_1 and n are constants depending on Reynolds number
	$Nu_\delta = Nu[A_1 + B_2 (sin\delta)^{m_1}]$	Where δ is the wind angle $A_1 = 0.42, B_2 = 0.68\ and\ m_1 = 1.08\ for\ 0° < \delta < 24°$ $A_1 = 0.42, B_2 = 0.58\ and\ m_1 = 0.9\ for\ 24° < \delta < 90°$
Natural Convection	$Nu = A_2 (Gr.Pr)^m$	Where A_2 and m are constants for various ranges of the Rayleigh number

Table I. Constants for calculation of forced convective heat transfer from conductors with steady crossflow of air

Surface	*Re*		B_1	*n*
	from	**to**		
Stranded all surfaces	10^2	$2.65\cdot 10^3$	0.641	0.471
Stranded $R_f \leq 0.05$	$> 2.65\cdot 10^3$	$5\cdot 10^4$	0.178	0.633
Stranded $R_f > 0.05$	$> 2.65\cdot 10^3$	$5\cdot 10^4$	0.048	0.800

Table II. Constants for calculation of natural convective heat transfer from conductors in air

Gr·Pr		A_2	m_2
from	**to**		
10^2	10^4	0.850	0.188
10^4	10^6	0.480	0.250

ANNEX G: SAG – TENSION ANALYSIS

TABLE G.1: PARAMETERS TO CALCULATE THE WIND FORCE ON THE CONDUCTORS [5, 57].

Height of conductors above ground(m)	Wind Speed (v)		Coefficient of height (k_w)	Coefficient of uniformity (C_w)	Standardized wind pressure on the conductor(N/m²) For conductor diameter	
	(m/s)	(km/h)			d>16, c=1	d<16, c=1.1
0 – 20	29.6	107	1.00	0.8	440	484
20 – 40	**33.5**	**120**	**1.27**	**0.75**	**525**	**577.5**
40 – 100	38.0	137	1.64	0.75	675	724.5
100 – 150	43.8	158	2.18	0.75	900	990

TABLE G.2: THE PARAMETERS OF NORMAL ICING [5, 57].

Icing area	Thickness of ice t (mm)	Density of ice ρ (kg/m³)	Weight of ice per 1 m length of the conductor (kg/m)	
			q_t measured on a rod with a Ø 30 mm	q on conductors with a Ø d (mm)
Light Icing Area (L)	17.0	400	1.0	0.361+0.0213d
Central Icing Area (S)	**27.6**	**400**	**2.0**	**0.959+0.0347d**
Heavy Icing Area (T)	36.1	400	3.0	1.638+0.0454d
Critical Icing Area (K)	$\sqrt{225+795.8q_t}-15$	400*	>3.0	$1.257\mathrm{t}(\mathrm{d}+\mathrm{t})10^{-3}$

* The largest bulk density of icing is being considered 900 kg/m³

TABLE G.3: RESULTS TENSION ANALYSIS VARIANT A, B.

θ_1 (°C)	w (N/m)	w_i (N/m)	w_w (N/m)	w_t (N/m)	F_{t1} (N/m)	F_{t2} (N/m)	T_1 (N)	T_2 (N)
-30	29.83	0.00	0.000	29.83	29.83	0.00	121,255.00	--
-5	29.83	22.77	49.91	**72.51**	29.83	22.77	121,255.00	**57,478.90**
-5	29.83	0.00	20.74	36.34	29.83	0.00	121,255.00	--
-5	29.83	22.77	0.00	52.60	29.83	22.77	121,255.00	--

TABLE G.4: RESULTS SAG ANALYSIS VARIANT A, B.

Section	Elevation* (m a.s.l.)		Distance** (km) d	Slope (rad) $\tan^{-1}\left[\frac{e_1-e_2}{d}\right]$	Level Difference (m) $h=lsin\theta$	Total length (m) $l_c=l+\frac{2Th}{wl}$	Sag (m) $S=\frac{wl_c}{8T}$
	e_1	e_2					
Röhrsdorf to Hradec	404	356	82	0.000585	0.20	352	8.1
Hradec to Chrást	356	362	82	0.000073	0.03	350	8.0
Chrást to Kočín	362	413	115	0.000443	0.16	352	8.0
Kočín to Slavětice	413	333	155	0.000516	0.18	352	8.0
Slavětice to Dürnrohr	333	231	96	0.001062	0.37	354	**8.1**

TABLE G.5: RESULTS TENSION ANALYSIS VARIANT C, D.

Section	Elevation* (m a.s.l.)		Distance** (km) d	Span L (m)	F_{t1} (N/m)	F_{t2} (N/m)	T_1 (N)	T_2 (N)
	e_1	e_2						
Röhrsdorf to Hradec	404	356	82	239	72.51	29.83	12,1255.00	---
Hradec to Chrást	356	362	82	316	72.51	29.83	12,1255.00	59,029.90
Chrást to Kočín	362	413	115	336	72.51	29.83	12,1255.00	58,071.13
Kočín to Slavětice	413	333	155	265	72.51	29.83	12,1255.00	62,216.09
Slavětice to Dürnrohr	333	231	96	322	72.51	29.83	12,1255.00	58,727.31

TABLE G.6: RESULTS SAG ANALYSIS VARIANT C, D.

Section	Slope (rad) $\tan^{-1}\left[\frac{e_1-e_2}{d}\right]$	Level Difference(m) $h=lsin\theta$	Total length (m) $l_c=l+\frac{2Th}{wl}$	Sag (m) $S=\frac{wl_c}{8T}$
Röhrsdorf to Hradec	0.000585	0.20	--	--
Hradec to Chrást	0.000073	0.03	316	6.3
Chrást to Kočín	0.000443	0.16	338	**7.3**
Kočín to Slavětice	0.000516	0.18	268	4.3
Slavětice to Dürnrohr	0.001062	0.37	326	6.8

*Approximated using google maps.

** Approximated using ENTSO-E map and [78].

ANNEX H: SKETCH OF SUPPORT STRUCTURES

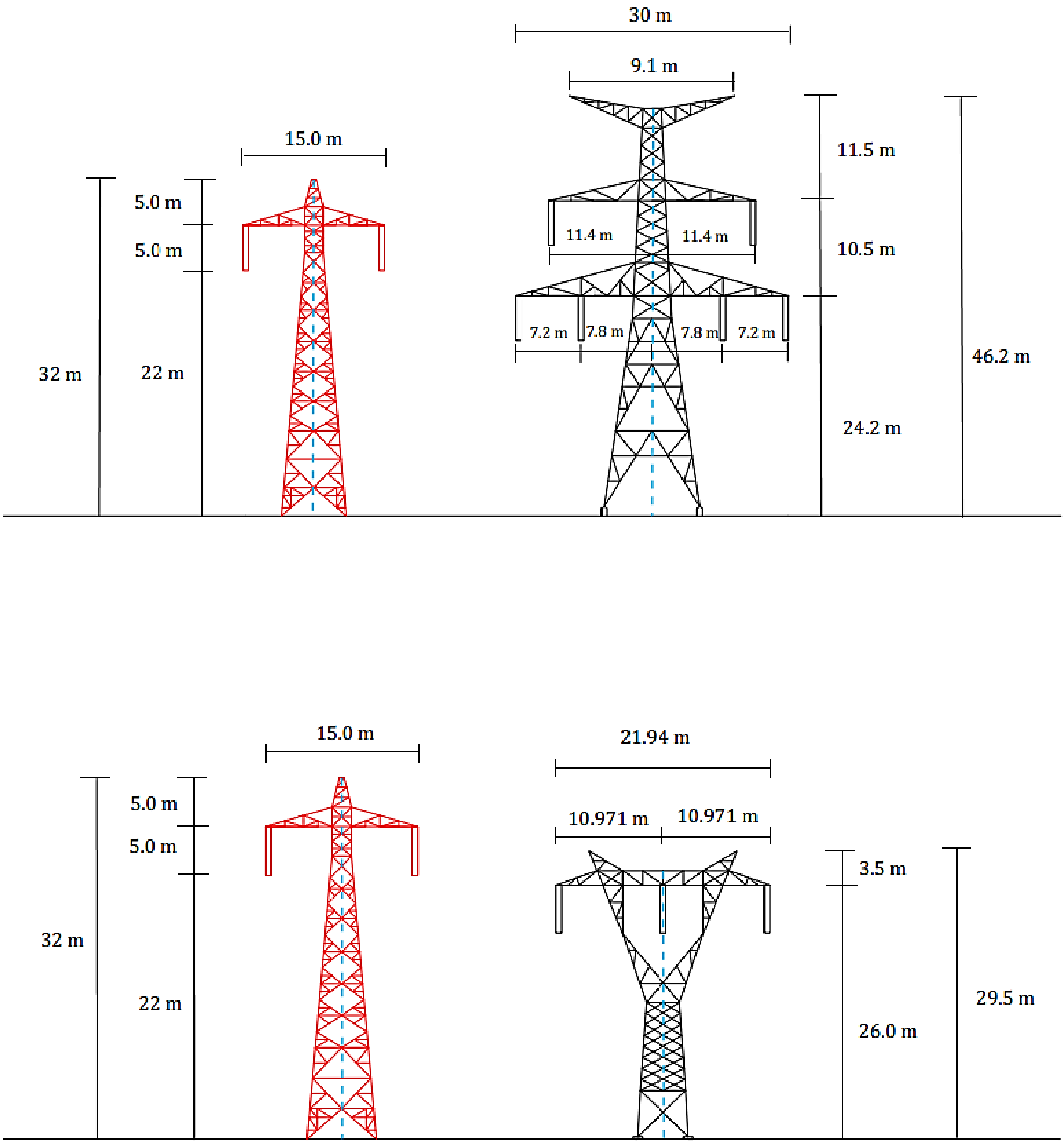


FIGURE H.1: VARIANTS A.1 AND A.2 (1,500 MW; ±400KV).

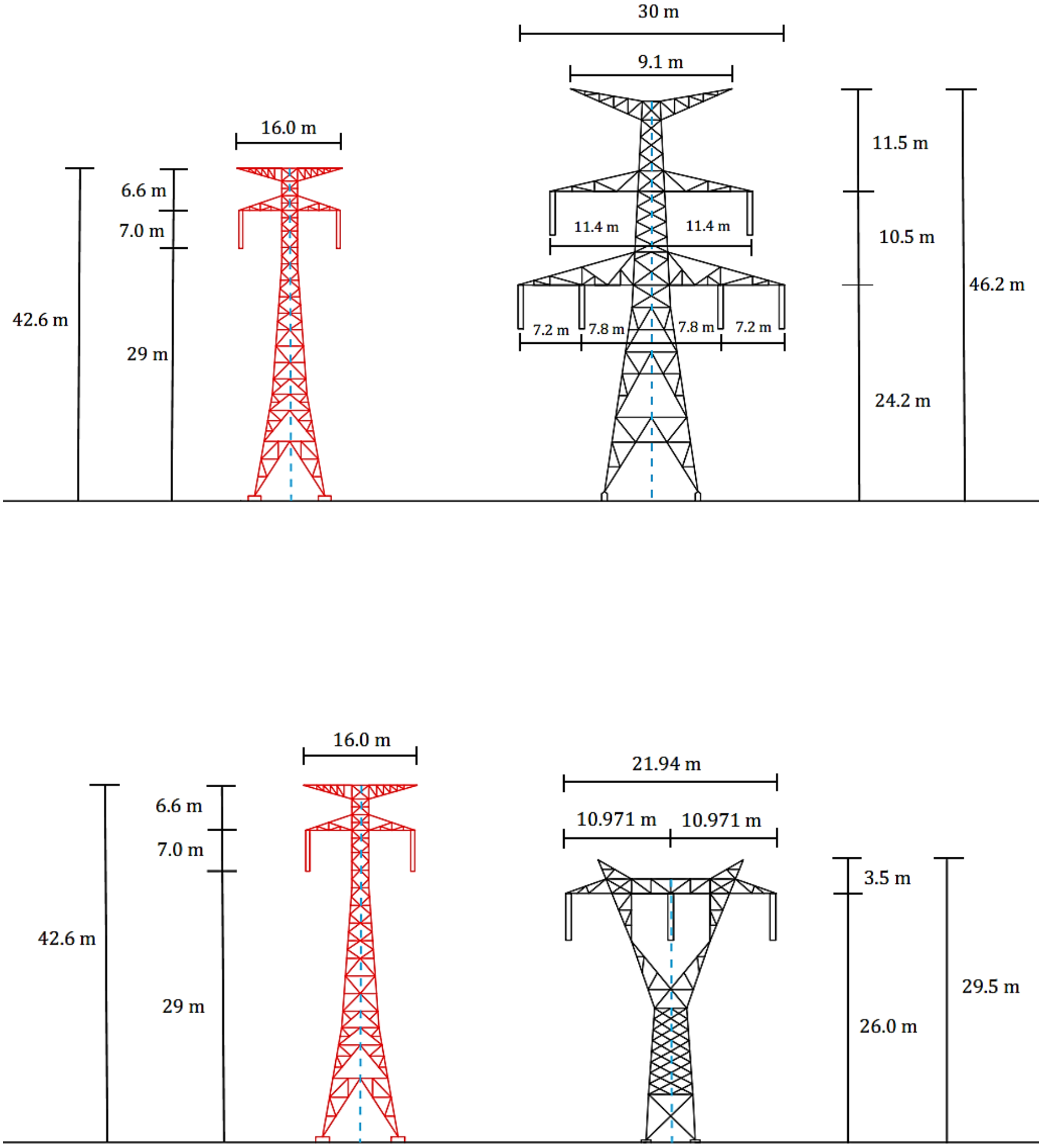


FIGURE H.2: VARIANT B (3,000 MW; ±500KV).

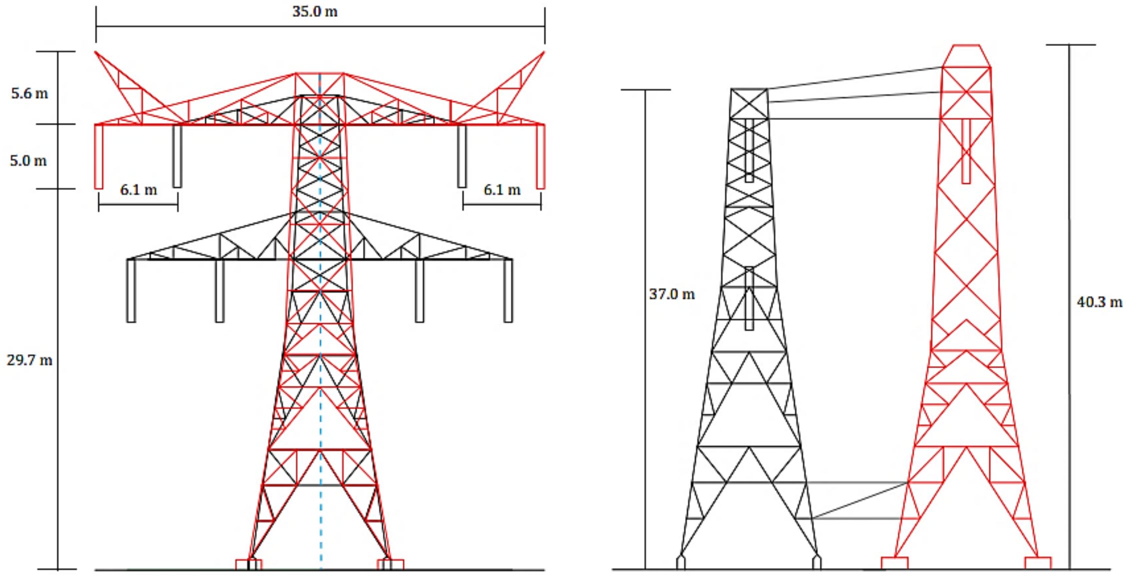


FIGURE H.3: VARIANTS C.1 AND C.2 (1,500 MW; ±400KV).

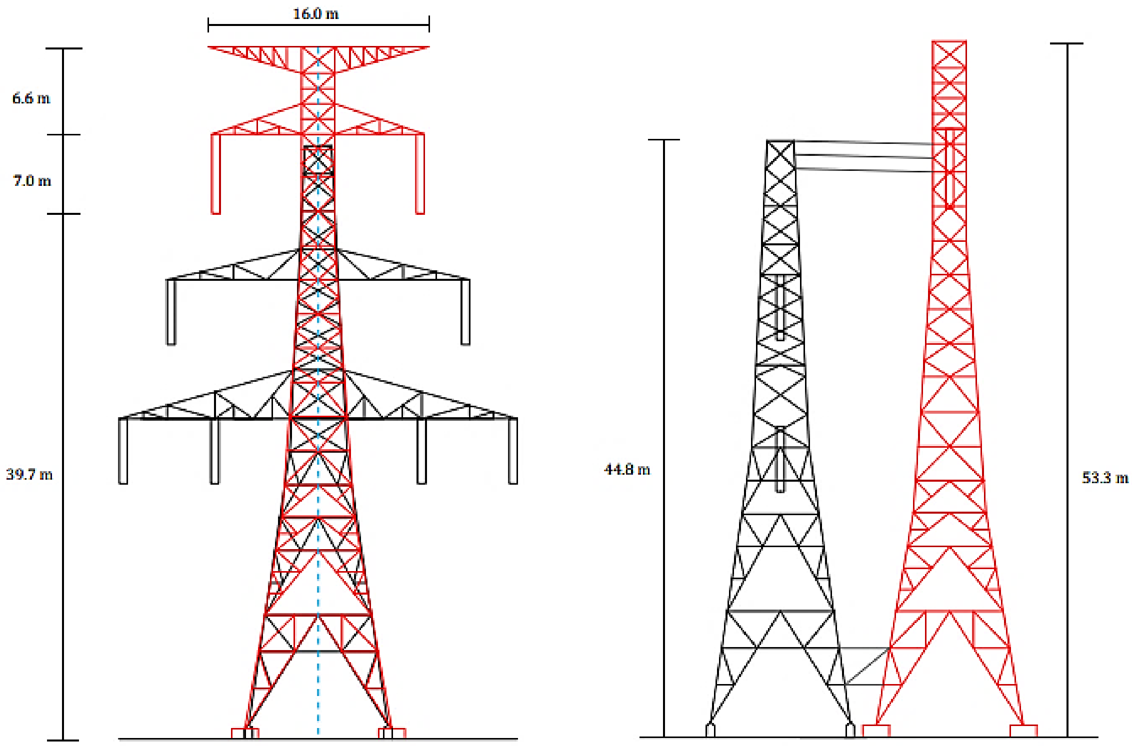


FIGURE H.4: VARIANT D (3,000 MW; ±500KV).

Annex I: Specific Cost

$$RFC = NPC * a(r, T)$$

TABLE I.1: RFC [MILLION CZK/YEAR]

Discount Rate	Variant A.1	Variant A.2	Variant B	Variant C.1	Variant C.2	Variant D
6%	2,020.07	2,291.76	3,070.53	2,190.08	2,461.77	3,289.95
8%	2,409.35	2,717.33	3,638.71	2,613.44	2,921.42	3,903.54
0.10	2,844.91	3,193.41	4,274.03	3,086.12	3,434.62	4,588.62
12%	3,324.39	3,717.40	4,972.97	3,605.39	3,998.40	5,341.23

TABLE I.2: SPECIFIC COST [THOUSAND CZK/MW/MONTH]

Discount Rate	Variant A.1	Variant A.2	Variant B	Variant C.1	Variant C.2	Variant D
6%	112.23	127.32	85.29	121.67	136.77	91.39
8%	133.85	150.96	101.08	145.19	162.30	108.43
10%	158.05	177.41	118.72	171.45	190.81	127.46
12%	184.69	206.52	138.14	200.30	222.13	148.37

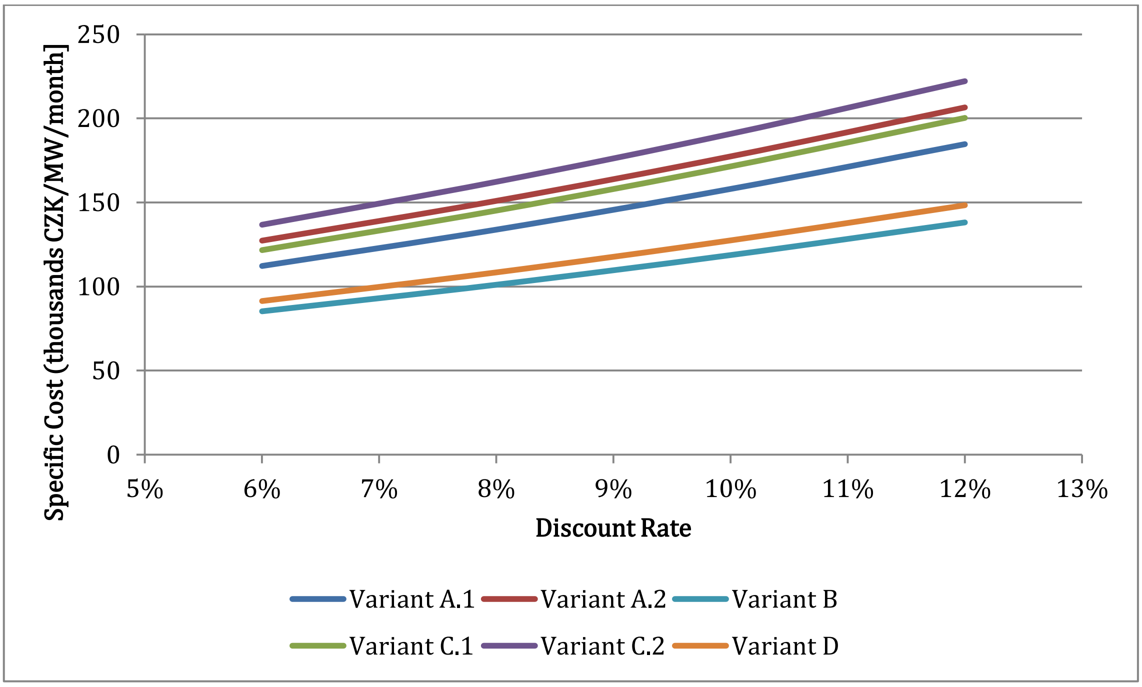


FIGURE I.1: DEPENDENCE OF SPECIFIC COST ON DISCOUNT RATE