1a. Introduction to HVDC Technology

Modules for Maturing HVDC Electric Transmission Knowledge

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Prerequisite Competencies:	1. Basic electric power engineering knowledge (in electric circuits and electromagnetic concepts) 2. Interest in the development of HVDC technology
Module Objectives:	1. Present historic expose of the development of HVDC 2. Introduce objectives and components of HVDC systems 3. Characterize principal types of HVDC configurations

Abstract

The introduction of commercial high voltage direct current (HVDC) technology allowed and made way for transmission of large quantities of electric power and interconnection of non-synchronous networks. HVDC is economically advantageous in case of long-distance power transmission, in particular where cables are used, e.g., for longer water crossings. The objective of this module is to introduce HVDC technology, based on either line commutated converter (LCC) or voltage source converter (VSC) technology. The aims of this module are to provide a background to the development of HVDC, basic understanding of technical aspects of high voltage direct current vs. high voltage alternating current (HVAC) transmission, including examples of installed HVDC schemes, and introduce major equipment categories. While introducing basic concepts, main components, and configurations for both LCC and VSC HVDC systems, this introductory module will focus on aspects of HVDC schemes based on LCC technology.

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Acronyms

AC	Alternating Current
DC	Direct Current
BJT	Bipolar Junction Transistor
C&P	Control and Protection
BOEM	Bureau of Ocean Energy Management
DLR	Dynamic Line Rating
DOE	U.S. Department of Energy
ENTSO-E	European Network of Transmission System Operators for Electricity
GTO	Gate Turn-Off thyristor
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IGBT	Insulated-Gate Bipolar Transistor
IGCT	Integrated gate-commutated thyristor
JSIP	Joint Statistical Innovation Project
MMC	Modular Multilevel Converter
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
MTDC	Multi-Terminal high voltage Direct Current
MTDCN	Multi-Terminal HVDC Network
NREL	National Renewable Energy Laboratory
LCC	Line Commutated Converter
OSW	OffShore Wind
PLC	Power Line Carrier
PNNL	Pacific Northwest National Laboratory
PWM	Pulse-Width Modulation
SCADA	Supervisory Control and Data Acquisition
SCR	Silicon Controlled Rectifier
STATCOM	Static synchronous compensators
TRL	Technology Readiness Level
VSC	Voltage Source Converter

Nomenclature

C	capacitance	[F]
f	frequency	[Hz]
I or i(t)	current	[A]
Id	dc current	[A]
P	active (or real) power	[W]
Q	reactive power	[var]
V or v(t)	voltage/electric potential	[V]
VLL	line-to-line voltage	[V]
Vd or vd(t)	dc voltage	[V]
Vdα	average dc-side voltage	[V]
ΔVu	commutation voltage drop	[V]
α	delay angle	[°]
ϕ	power factor ang	[°]
ω	angular frequence	[rad/s]

1a-1 Introduction

1a-1.1 Motivation

The electrical landscape in most of industrialized world, including in the Unites States, is undergoing significant changes requiring extensive expansion of electric power transmission capacity. The electric utility industry stands at an inflection point where it simultaneously experiences a higher rate of load growth than in a long time and, in many parts of the industrialized world, an emphasis on decarbonization of the electric generation industry. This results in a desire to strengthen interconnections between regions and accessing remotes renewable energy resources. A workable viable option of achieving such a modernization of the electric power systems is by increased utilization of high voltage direct current (HVDC) transmission links.

HVDC transmission provides a highly flexible and efficient method of transmitting large quantities of electric power over long distances. Other examples of HVDC applications include interconnection of non-synchronous power grids, connection of offshore wind power to onshore substations, and increase transfer or power across limited right-of-way paths. By supporting interconnection of grids and integration of renewables, HVDC can play a vital role in enabling the carbon-neutral energy system of the future.

This vision of transforming today's mainly passive electric grid towards a controllable electric network provides a path towards the electric power system of the future, a system that supports improved reliability, resilience, and security. This sets forth a vision of the power system of the future, a system that is innovative, reliable, and environmentally sensitive. This can be achieved by increased utilization of high voltage direct current, a proven technology, which presently is experiencing an unprecedented global demand.

1a-1.2 Development of HVDC

The development of high voltage direct current (dc) transmission can be traced back to development of direct current and alternating current technologies, including the 'war of currents,' during the last decades of the 19th century. The modern history of HVDC technology includes early projects with current source converters built with mercury-arc valves via thyristor valves to fast switching high power transistor-based semiconductors. The history of HVDC development also includes development of multi-terminal HVDC schemes, with earlier versions using current source converters with thyristor valves and more modern schemes using voltage source converters with insulated-gate bipolar transistor (IGBT) valves.

HVDC schemes consisting of converter terminal, including an electronic controllable valve based on semiconductor technology, and a dc conductor (overhead line and/or cable) can transfer large quantities of electric power within or between alternating current (ac) electric systems. An interconnected ac network operated with the same frequency is referred to as a synchronous system and the HVDC scheme can then be operated in parallel with the ac system. HVDC schemes can also interconnect non-synchronous networks, i.e., two ac system operated with different ac system frequencies. Main components of a HVDC converter station include HVDC valves (converters), converter transformers, ac switchyard, and dc switchyard.

HVDC schemes between two non-synchronously operated ac power systems can also be constructed with the two converter terminals next to each other in the same switchyard and connected with a very short conductor, which are referred to as back-to-back schemes.

An advantage of HVDC is that the transfer of power can be controlled. The transfer of power between HVDC stations can be reversed and hence take place in either direction. Rationales for selecting HVDC schemes over 'traditional' ac transmission alternatives can include both economic and technical considerations.

1a-1.3 Objective

The objective of this module (Module 1a) is to provide an introduction to HVDC technology, based on either line commutated converter (LCC) and voltage source converter (VSC) technology. The introduction of commercial HVDC technology allows for interconnection of non-synchronous power systems and is economically advantageous in case of long-distance power transmission, in particular where cables are used, e.g., for longer water crossings. This module provides a basic understanding of technical aspects of high voltage direct current vs. high voltage alternating current (HVAC) transmission, including examples of installed HVDC schemes, and introduce major equipment categories. While this module introduces basic concepts, main components, and configurations for both LCC and VSC HVDC systems, this introductory module will focus on aspects of HVDC based on LCC technology.

1a-1.4 Structure of Module

This module, Module 1a 'Introduction to HVDC Technology,' begins with a historic expose of the development of HVDC technology, including an introduction of semiconductor components. This introductory part is followed by a section on consideration when deciding between use of direct current vs. alternating current for high voltage transmission applications. The next two sections present some fundamental concept related to line commutated converter and voltage source converter, followed by a section on major equipment categories for LCC and VSC applications. This module is concluded by a summary listing main learning points followed by a couple of questions and problems to review and reinforce main learning points.

Other modules, like Module 1b 'Introduction Guide for HVDC Transmission,' Module 1c 'Introduction to HVDC for offshore wind', and Module 7a 'Point to point HVDC systems' provide additional and more in-depth understanding of HVDC applications, configurations, control modes, and provides insight into some use cases. Since all early HVDC applications in North America were and also most present installations are based on line commutated converter technology, this module will focus on the history, development, fundamental concepts, and application of LCC HVDC technology.

1a-2 Historic Expose

The below abridged historical expose does not provide a complete historic account of the development of high voltage direct current electric power transmission systems but provides a brief introduction and some background information for this development.

1a-2.1 Early History

The history of electricity includes e.g. the invention of the electric battery (voltaic pile) by the Italian physicist and chemist Alessandro Volta around 1800 and invention of the solenoid by the French physicist and mathematician André-Marie Ampère in the first part of the 19th century. Volta developed the terms capacitance and voltage to describe the associated electrical concept [1]. The SI unit of electric potential, volt (V), is named after him. Ampere laid the foundation for electrodynamics by showing how two parallel wires carrying electric currents attract or repel each other [2]. The SI unit of electric current, ampere (A), is named after him.

Figure 1a – 1: Alessandro Volta [1]

The English physicist and chemist Michael Faraday, studying both electrochemistry and electromagnetism, contributed to the study of electromagnetism, including developing simple conceptual models for what later became the electrical generator, motor, and transformer. Faraday participated in a travel to continental Europe including France and Italy, where he met with Alessandro Volta and André-Marie Ampère [3]. Faraday invented the first electrical generator in 1831 [4], in which he converted the mechanical energy of a rotating copper disc to electrical energy. The SI unit of capacitance, farad (F), is named after him. Maxwell later developed a mathematical formulation for Faraday's ideas of electrical fields.

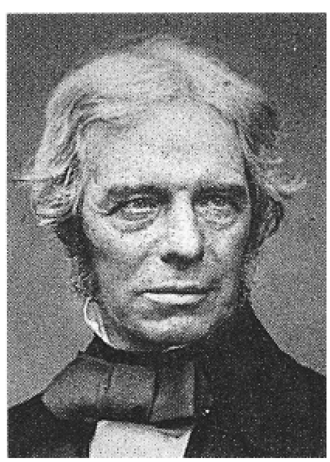

Figure 1a – 2: Michael Faraday [3]

André-Marie Ampère is together with Danish physicist Hans Christian Ørsted sometimes considered the founders of our understanding of electromagnetism. The phenomenon of electromagnetism was further developed and described by Scottish physicist and mathematician James Clerk Maxwell in the publication 'A Treatise on Electricity and Magnetism' in 1873, where he demonstrated that electric and magnetic fields travel through space as waves moving at the speed of light. The set of partial differential equations, referred to as Maxwell's equations, form the foundation of classical electromagnetism. The modern form of these equations is in its most common formulation credited to Oliver Heaviside, hence sometimes referred to as Maxwell-Heaviside equations [5]. All this set the stage for practical use of electricity.

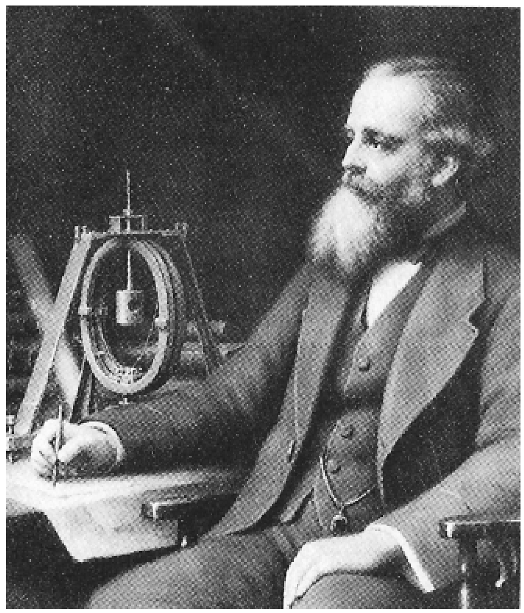

Figure 1a – 3: James Clerk Maxwell [6]

1a-2.2 Pearl Street

The late 1870s and early 1880s saw the introduction of outdoors use of arc lamp lighting. An arc light is as the name suggests a lamp that produces light, with a spectrum close to that of sunlight, via an electric arc between carbon electrodes in air [7]. The relatively harsh, intense light from arc light lamps meant that their practical application usually was limited to lighting outdoor areas or in large indoor spaces. Arc lighting continued to be in use for applications requiring a high intensity point light for a long time [7]. Around 1880, street lighting based on arc lighting systems became operational in the United States and Europe.

In October 1879, the American invertor Thomas Alva Edison successfully tested an incandescent light bulb based on a high resistance carbonized cotton filament, and the era of electric light started [8]. After inventing the incandescent lightbulb, Edison and his team turned their attention to design of the required generator or dynamo, which could supply constant voltage to the envisioned lighting system with parallel connected incandescent lightbulbs [8]. In August 1880, Edison filed a patent application 'System of Electric Lighting,' which was issued as US patent the following year. The invention describes a system with conductors carrying current from a central station, acting as source of electric energy, to electric lighting. The term ‘central station’ was adopted from the railway terminology [9].

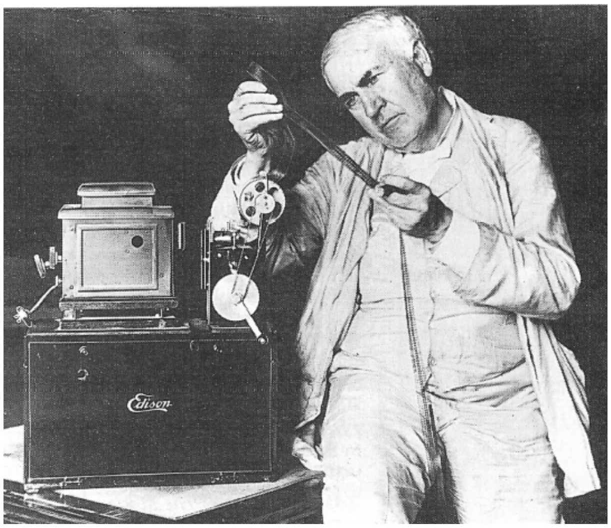

Figure 1a – 4: Thomas Edison [10]

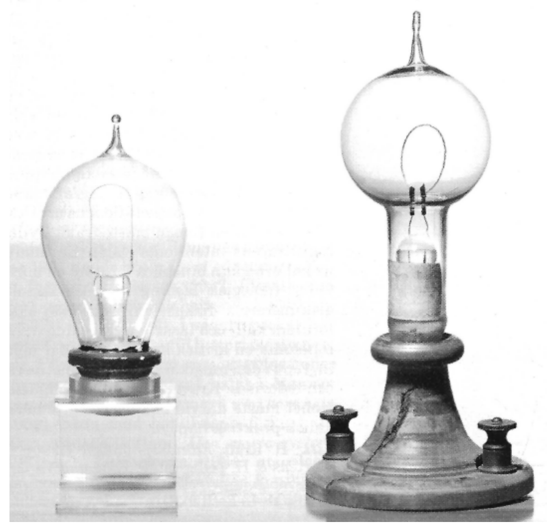

Figure 1a – 5: Some of Edison’s Lightbulbs [10]

Edison first demonstrated his concept of an incandescent electric lighting system with a central station at Holborn Viaduct in London in January 1882 [8]. This was a temporary installation, and later the same year, Edison designed the first permanent commercial power plant, with an underground distribution network, the Pearl Street station in lower Manhattan. The initial systems were based on a generator with a few distribution wires delivering electricity. Pearl Street station started generating electricity on September 4, 1882, with six 100 kW direct current (dc) dy7namos, initially serving 400 lamps at 82 customers [11].

In 2011, IEEE commissioned a plaque which reads, “Thomas Alva Edison established the Edison Electric Illuminating Company of New York, now Consolidated Edison, to commercialize his 1879 incandescent lamp invention. On 4 September 1882, Edison’s direct current (dc) generating station at 257 Pearl Street, began supplying electricity to customers in the First District, a one-quarter square mile (0.65 square km) area. This installation was the forerunner of all central electric generating stations.” By this, Edison conceptualized and then constructed the first electrical distribution neighborhood network: the Pearl Street Network [11].

Pearl Street consisted of a single generating station delivering power at 110 V dc, but there were no transmission lines or transformers since it was a dc network. The first motor is said to have been put on the system supplied by the Pearl Street station in the fall of 1884 [11]. Pearl Street Station was also the world's first cogeneration plant. While the steam engines provided grid electricity, Edison made use of the thermal byproduct by providing steam heating to local manufacturers and nearby buildings on the same Manhattan block. The location of Pearl Street station was selected carefully in the financial heart of New York near Wall Street. The station burned down in 1890, destroying all but one dynamo that now is kept in the Greenfield Village Museum in Dearborn, Michigan.

1a-2.3 AC vs. DC

There was still no method to achieve longer-distance transmission of electric power due to the high cost of copper conductors and high line losses. The customers of the dc systems had to be within a radius of a mile or two from the central (direct current generating) station. In Europe, high-voltage direct current transmission was invented and started to be used in 1889. These dc transmission systems were invented by the Swiss engineer René Thury and continued to be in service for more than 30 years [9]. The Thury system used generators in series to attain high transmission voltages to supply series connected dc motors driving loads either directly or using motor-generator sets [12]. The Moutiers-Lyon system, which was in operation between 1906 and 1936, in its final configuration transmitted 20 MW over 200 km, including 10 km of underground cable using eight series-connected generators for a total voltage of 150 kV [13].

Longer distance transmission of electric power using alternating current became feasible first with the development of transformers for stepping-up or stepping-down voltages. The American inventor and engineer William Stanley developed the first practical transformer, and in 1886 Stanley designed and installed, supported by George Westinghouse Jr., the first practical single-phase ac transmission system with transformers in the United States at Great Barrington, Massachusetts [14]. In 1886, the Serbian American engineer and inventor Nikola Tesla tried to sell his ac power system to investors in New York City, but it failed in a city which is already heavily invested in dc power systems. An important reason for this is that no one yet had invented an efficient ac electric motor [15].

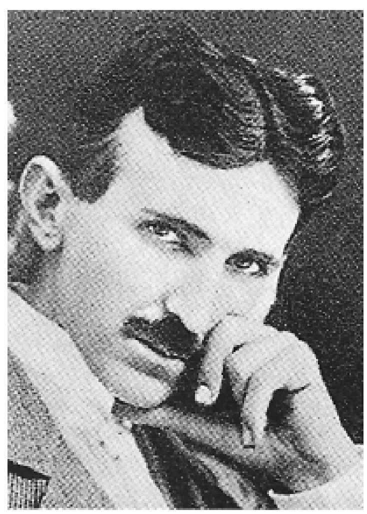

Figure 1a – 6: Nikola Tesla [16]

In November of 1887, Tesla filed a series of seven US patents in the field of polyphase ac motors, power transmission, generators, transformers, and lighting. The U.S. Patent Office approved and issued these important and valuable patents without challenge [8]. The American engineer and entrepreneurial industrialist George Westinghouse, recognizing the importance of these patents for development of large scale alternating current power systems, purchased the seven patents and employed Tesla to pursue the development of ac power systems [17].

Westinghouse Electric Company could now manufacture and market ac power systems, thereby setting the stage for whether alternating current or direct current would be the technology to power the electrical industrial revolution that started during the last years of the 19th century [17]. This also became a starting point for 'the war of the current,' where the Edison Companies early took on the offensive by claiming that alternating current was inherently unsafe.

In 1888, multiple inventors, including Tesla, develops and improves various designs of polyphase ac motors. During the early 1890s, the American mathematician, engineer, and philosopher Charles Proteus Steinmetz developed an improved mathematical understanding of ac power systems [15]. The 1890s thereby saw a breakthrough for three-phase system which provided a means, both technical and at an acceptable cost, of transmitting electricity over long distances. The Russian Mikhail Dolivo-Dobrovolsky, the American Nikola Tesla, the Italian Galileo Ferraris, and the Swede Jonas Wenström all pioneered polyphase ac power systems by developing three-phase electrical generators and motors. The triumph of the three-phase system was displayed in Europe at the International Electro-Technical Exhibition of 1891, in Frankfurt am Main, Germany, where Dolivo-Dobrovolsky used this system to transmit electric power at the distance of 176 km with 75% efficiency [18].

Mikhail Dolivo-Dobrovolsky in Russia and Jonas Wenström in Sweden both independently developed and received patents for three-phase electric power systems in 1890 [19]. The world's first complete commercial three-phase power system which included all the fundamental components of a modern ac power system, i.e., generator, transformer, transmission line, and motor (load) was installed from a hydro power station at Hällsjön to mines at Grängesberg, Sweden in 1893. This three-phase 9.5 kV system transferred 400 horsepower over a distance of 15 km. Wenström corresponded with Edison, including about his invention of electric light [20]. The transmission line corridor between Hällsjön and Grängesberg was in 1997 re-purposed as the world's first Voltage Source Converter (VSC) HVDC transmission system.

1a-2.4 War of the Currents

In the late 1880s and early 1890s there was competition between Thomas Edison's direct current and George Westinghouse's alternating current electric power transmission systems, sometimes referred to as 'the war of currents' [21]. Edison, while stating that low-voltage dc was perfectly safe, condemned ac voltages over 300 V and was in favor of banning ac altogether or at least limit voltages to no more than 300 V [17]. At the same time. the American engineer Harold Brown went as far in his activism against alternating current that he travelled around and electrocuted dogs, calves, and also an old horse on stage. Brown pushed to have the first electric chair, which in 1890 was used in the state of New York, to be powered with ac current [17].

The first industrial application of ac power transmission took place in 1891 when Westinghouse installed an approximately 5 km 3 kV single-phase from a water wheel to a mill in Telluride, Colorado. The ore crusher was installed at an altitude of over 9,000 ft (approx. 2,700 m) and was powered by a 100-horsepower (approx. 75 kW) synchronous generator [17]. As noted above, the same year three-phase power transmission from a generating station at Lauffen am Neckar was shown at the 1891 International Electrotechnical Exhibition in Frankfurt am Main, Germany [22]. This successful field trial supported the establishment of three-phase ac as the concept for long-distance transmission.

At the 1893 Chicago World's Fair, which was also known as the Columbian Exposition in celebration of the 400th anniversary of Columbus first voyage, both General Electric and Westinghouse bid for lighting the fairgrounds. Westinghouse, with their ac transmission technology, were able to underbid General Electric by more than one half [17]. Use of electric light to illuminate buildings and fairgrounds at the 1893 World's Fair turned the exhibit into a 'city of light,' and thereby demonstrating that ac power systems were both practical and available [17]. The Electricity Building at the Chicago World's Fair was the first time an exposition had set a whole building apart for electricity, which illustrated how far development of electricity had advanced since the Pearl Street station only eleven years earlier [23].

In 1895, Westinghouse and Tesla built the first hydro-electric power plant in Niagara Falls between U.S. and Canada. The Adam's Power Station, later known as Niagara Power Station No. 1, would in 1990 reached its full capacity of 50,000 horsepower (37 MW) of electricity generation capacity [24]. Even after the Niagara Falls hydro-electric power project had establish alternating current as the solution for long-distance transmission, direct current continued to be used for e.g., local distribution of power to customers as well as electric railways and other traction applications.

Many loads, like street car traction systems used dc motors, hence the period 1892-1893 saw the invention of synchronous rotary converters. Use of ac slip rings at one end and a dc commutator on the other end allowed the synchronous rotary converters to supply street cars with dc current from an ac system [17]. Direct current still dominated the use of electric power in the U.S. that catalogues of electrical manufacturers coined the term 'city current' for equipment meant for use by customers in local dc distribution systems [25].

While the war of currents was won by alternating current with the development of practically useful transformers to convert between different voltage levels, the first commercial system for long-distance transmission of direct current had already been introduced in Europe in 1889 [26]. Such a system was put into service in Italy, for supplying power to the city of Genoa from the Gorzente River hydro turbines at 6 kV. Genoa's Thury system for dc power transmission was upgraded in stages to finally serve 630 kW at 14 kV over a circuit distance of 120 km [13]. The Thury dc transmission scheme at Lyon-Moutiers, in service between 1906 and 1936, was a 200 km dc transmission, which in its final configuration was 20 MW at ±75 kV [27].

With introduction of outdoors use of arc lamp lighting and the development of direct current systems by Edison, the electrification of the U.S. began. As the use of electric power increased, the disadvantage of changing not being able to use transformers to change the voltage and thereby allowing construction of larger networks and transportation of electric energy over larger distances became obvious. This was resolved with the inventions by Tesla, and the development of alternating current systems allowed for use of simpler and more robust electric motors [28]. When Tesla was given the contract to provide lighting for the Chicago World's Fair in 1893, this represented a key victory for alternating-current systems over direct-current and became a turning point in the war of currents. This started the electrification of the world.

1a-3 HVDC Development

1a-3.1 Early AC-to-DC Power Conversion

As noted above and discussed in more detail below, while alternating current prevailed in the ‘war of currents,’ the direct current option was never really abandoned. The benefits of having two conductors (and in some cases only one cable) and not having to deal with reactive power were reasons for some to continue looking at direct current for transmission of large quantities of electric power over long distances. One of them was, as noted above, René Thury who pioneered dc transmission using series connection of multiple dc generators, in the 1890s. The only option for conversation from ac to dc at that time was rotary converters, which required relatively low speed for satisfactory commutation. Hence, installed Thury system used low speed dc machines driven by hydro turbines [12].

Experiments with high voltage dc transmission based on rotary converters were conducted in multiple geographical locations in the beginning of the 20th century but mechanical complexity and expense of these systems deferred major installations of dc transmission. Synchronous converters, also known as rotary converters, were a vital link in the transition from early dc systems to ac distribution systems. These rotary converters provided an essential link between the ac system and older dc installations during several decades [29]. In 1963, there were still 23 rotary converters in Manhattan but by 1976 only two were remaining, both which were retired the following year. This was still not the end of dc supply, and the last dc supply cable in Manhattan was not cut until November 2007 [30].

After rotary converters, mercury-arc valves were invented, developed, and used to convert between ac and dc. The patent for mercury-arc valves was issued in 1901 and grid control allowing for both rectification and inversion of currents were developed between World War 1 and 2. A breakthrough for conversion technology came in 1928 with the development of high-power electronics in the form of mercury arc rectifiers with grid control. General Electric led the early research in the U.S., but the U.S. programs soon favored the newer thyratron tube converters while European research continued working with mercury valve concepts [25]. Another milestone was when Uno Lamm (more information about Uno Lamm is provided in the following section) was granted a patent for grading electrodes for mercury-arc valves, which improved their voltage distribution and withstand capabilities [12]. Mercury arc rectifiers received their name from the ‘pool’ of mercury at bottom of the tank serving as a cathode.

During the 1940s experimental high power dc transmission links based on mercury-arc valve technology were developed and came into existence in Germany, Sweden, and the U.S. Already in 1941, the world’s first commercial HVDC transmission system, a 60 MW ±200 kV 115 km HVDC scheme between a generating station on the river Elba and Berlin, was ordered in Germany. Due to the war, the system was never commissioned, and after the second world war, the system was disassembled and moved to the Soviet Union where it was used as a research facility [12]. In Sweden, a 60 km 6.5 MW 90 kV experimental HVDC link between Mellerud and Trollhättan, in the western part of the country, was energized in 1946 [12].

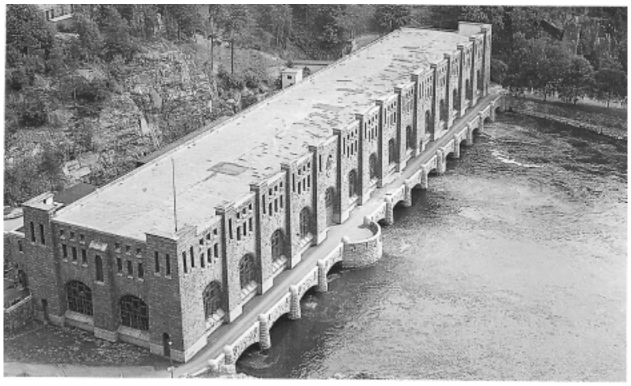

Figure 1a – 7: Oliden Hydro Power Station in Trollhättan [31]

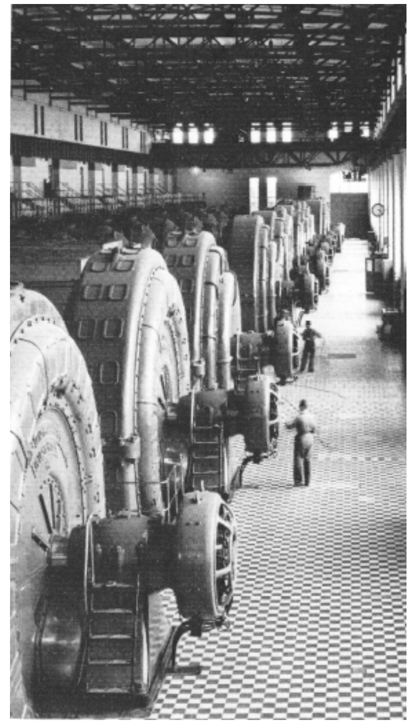

Figure 1a – 8: Generator Hall at Oliden Hydro Power Station (Trollhättan) [31]

As noted from above, high voltage dc transmission schemes can take several different forms. While early HVDC systems, built until the 1930s, were effectively rotary converters and used electromechanical conversion with motor-generator sets connected in series on the dc-side and in parallel on the ac-side, all HVDC systems built since the 1940s have used electronic (static) converters [28]. Following the invention and development of solid-state semiconductors, both rotary converters and mercury-arc valves became 'extinct.' Today all HVDC converters are based on solid-state semiconductor valves, which will be discussed in some more detail below, but first some background including an introduction of the man who became known as the 'Father of High Voltage Direct Current' power transmission.

1a-3.2 Uno Lamm

In 1928 a young engineer, Uno Lamm, was assigned the problem of solving the so-called arc-back (or backfire) of mercury-arc valves. Backfiring resulted in that mercury-arc valves instead of in a controlled way conducting or blocking the flow of current as intended experienced a short-circuit resulting in the valve conducting electric current in an uncontrolled way. The attempts to solve the problem of current taking 'the wrong direction' would continue to occupy engineers for many decades. Uno Lamm wrote that he "worked on it for 35-40 years without ever being able to fully remove the backfire phenomenon. My only consolation was that none of the competitors were able to do it either" [32].

Application of mercury-arc valves was at this time limited to voltages up to 1,500 V, and used e.g., in the electrochemical industry. From a physical point-of-view there were no upper limit for the voltage these converters could handle, so use of mercury-arc valves for high voltage dc applications were already in the minds of the engineers [20].

Figure 1a – 9: Uno Lamm [32]

Uno Lamm who had received his Master of Science degree from the Royal Institute of Technology (KTH) in Stockholm in 1927, already during his first year at the electrical equipment manufacturing company ASEA, came up with an idea that would eventually solve this problem. The solution included adding grading electrodes between the anode and control grid. In 1929 Lamm became manager of the project at ASEA to develop a high-voltage mercury-arc valve. He continued studying part time while developing the mercury-arc valve and received his Ph.D. from the Royal Institute of Technology in 1943 [33].

Uno Lamm, who won several professional awards has often been referred to as the 'Father of High Voltage Direct Current' power transmission. He himself said that there is no greater pleasure in what one can be considered to have contributed than to see all those who have contributed, taken over, and further developed them [20]. Lamm also coined the term 'transistor' for a network of resistors that would have the same function as a transducer. One of the inventors of our present-day transistors, William Schockley, said that had heard a Swede using the word, and he thought it fit his invention as well [28].

In 1938, Uno Lamm recruited another of the HVDC pioneers, Erich Uhlmann whom was of Jewish decent and had to flee Germany. His wife and two children who were still in Germany managed to get travel permits, just before the second world war would have made any such attempt impossible and joined Erich Uhlmann in Ludvika [20].

After the occupation of Norway in 1940, nazi-Germany used the hydroelectric power plant, facilities at Rjukan to produce heavy water as a component in their program to develop an atomic bomb. During the war, ASEA made a delivery to the mercury-arc converters to Rjukan. The fitter Harald Jansson, whom Uno Lamm described as one of the finest people he had met in his life, together with Uno Lamm decided not to apply recently found fixes related to the operation of the mercury-arc converters that otherwise could have made these mercury-arc converters at Rjukan fully operational [20].

1a-3.3 Vattenfall and ASEA

Long-term industrial relationship, resulting in an intimate collaboration between a large state customer and a large manufacturing company has been referred to as a 'development pair' [34]. The story of HVDC includes such a 'development pair' consisting of the Swedish State power utility Kungliga Vattenfallsstyrelsen (Royal Board of Waterfalls) founded in 1909, later known as Vattenfall, and the Swedish electrotechnical company Allmänna Svenska Elektriska Aktiebolaget (ASEA) founded in 1883. The collaboration included multiple key concepts, such as technology, cooperation, development, and demonstration of novel electrotechnical technologies.

The collaboration in Sweden between the power utility Vattenfall and the electrotechnical equipment manufacturer ASEA became an essential part of the development of high voltage direct current for commercial applications. The collaboration between a power conversion equipment manufacturing and a utility during the first half of the 1900s was an important factor during the development of both alternating current and direct current for electric bulk power system applications. This collaboration has been described as both intimate and reliable [35]. ASEA AB of Sweden, in 1988, when merging with Brown, Boveri & Cie (BBC) of Switzerland become Asea Brown Boveri, later only referred to as ABB. ABB's power grid business merged with Hitachi in 2020 and is today doing business as Hitachi Energy.

In the beginning of the 1940s Vattenfall were developing plans for how best to transport power from the hydro power station being built in the norther part of Sweden to the load centers in the south. Both alternating and direct current options were evaluated for the development of this bulk power transmission system. Several possible solutions, both internationally and in Sweden, were discussed in the period between the first and second world wars. In fact, in 1933 two competing Swedish prototypes were presented [34]. One of them was developed by ASEA, and during the second world war ASEA reached out to Vattenfall in search of a project to test their HVDC transmission solution in an operating power system.

With the ultimate build-out of hydro power in the northern part of Sweden, this would result in transporting some 10,000 MW over a distance of about 1,000 km (approx. 620 miles). Both high voltage alternating current and high voltage direct current alternatives of achieving the above objective were discussed but when decision had to be made in the mid-1940s it was considered too early to introduce HVDC in an operating power system [31]. The decision instead became to build 380 kV ac transmissions lines. When the first part of the 380 kV ac system taken into operation with full voltage on April 1, 1952, this was then the highest transmission voltage in the world [35]. While continuing building the 380 kV bulk power transmission system, the idea of developing high voltage dc transmission continues and in January 1947, Vattenfall re-established contacts with ASEA to develop a HVDC system [34].

Figure 1a – 10: Standard Straight-Line 380 kV Transmission Tower [31]

During this period Vattenfall built a laboratory for testing mercury-arc valves. Work at the laboratory was based on an agreement between Vattenfall and ASEA where Vattenfall provided the laboratory facility, electric power for the experiments, and operational staffing while ASEA provided experimental equipment, measurement equipment, and technical expertise. No monetary transactions took place between the two entities, although Vattenfall were promised an advantageous price when purchasing the first HVDC facility [20].

While Vattenfall began constructing the 380 kV ac system, tests continued at this joint laboratory facility, including building of a test HVDC transmission facility between Trollhättan and Mellerud in western Sweden. The location of the first trial converter station at Trollhättan was chosen based on the adjacent hydro power plant and a 50 km, 6.5 MW, 90 kV HVDC transmission was operation in 1945 [36]. Lamm, who had supported cautious development of the HVDC technology soon got an opportunity to do so with the development of a high voltage dc cable between the mainland and the island of Gotland, to be expanded in several phases.

1a-3.4 Gotland

At the end of the 1940s it was decided to build the world's first commercial HVDC transmission between the Swedish mainland the island of Gotland (in the Baltic) [31]. This HVDC system included a 90 km 100 kV underwater cable and development of the converter stations in three phases, 10, 20, and 40 MW. The direct current alternative was economically advantageous since an alternating current cable would have resulted in losses of up to 30%. When the contract was going to be signed in 1950 the General Director of Vattenfall Åke Rusck asked Uno Lamm is he was sure that it (the HVDC system) would work. Lamm answered no, I have never said that for sure. We still have nothing that works but we think there is a great chance that we will be able to overcome the last obstacles. With that, Rusck laughed and signed the contract [34].

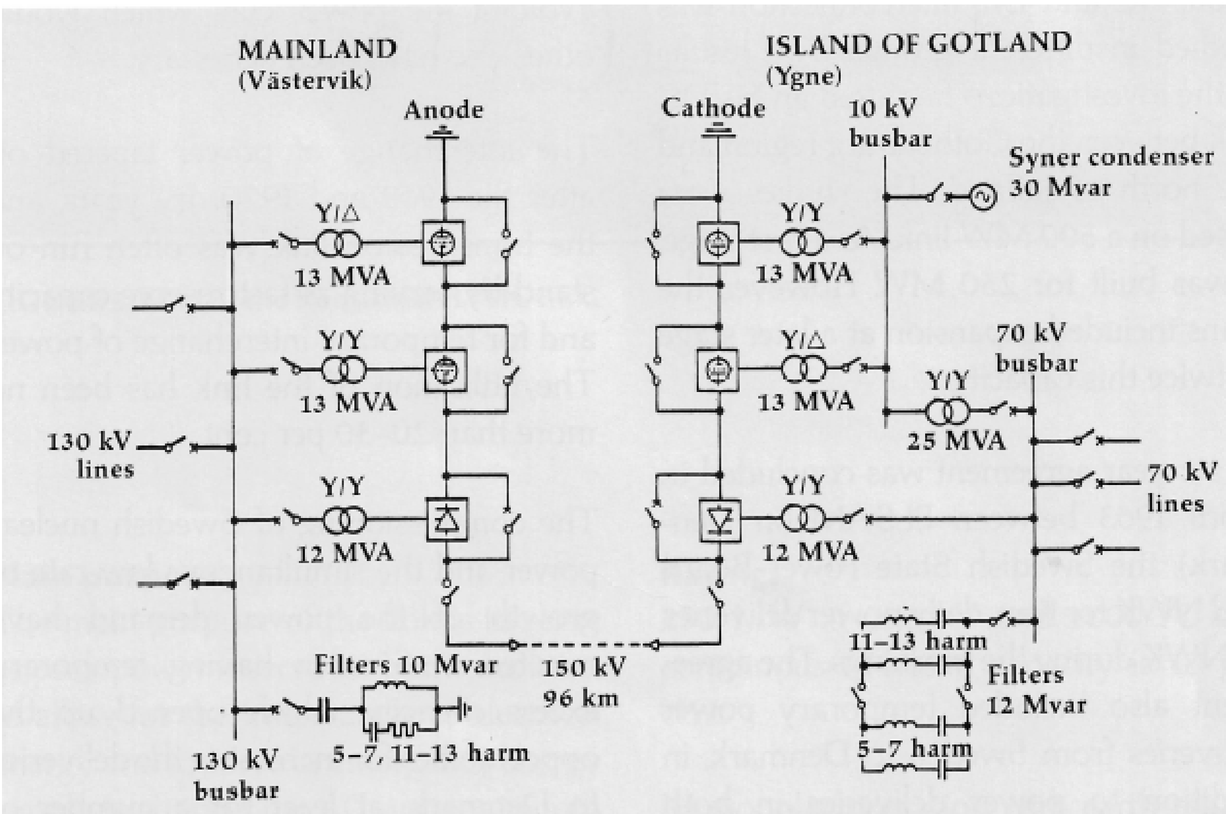

Figure 1a – 11: One-Line Diagram for the Gotland HVDC Scheme [37]

Uno Lamm commented that it was a fortunate situation that Sweden, in this case the island of Gotland, needed a relatively reasonable level of electric power transfer capacity, while still economically attractive. The price of electricity would be halved when the HVDC link was commissioned and initiated commercial operation in 1954 [20] and the electric customers on the island could access hydro power from northern Sweden. The initial installation was built with mercury-arc rectifier converters in a monopolar topology, often installing earth electrodes nearby the converters stations and using the sea as return conductor.

Issues such as earth return, i.e., use of electrodes placed in the vicinity of the converter stations and use of ground via the sea water as earth return allowing for installation of a single dc cable, was discussed and later used for the initial HVDC system installed between the mainland the island of Gotland. To enable use of sea water to form an earth return path for the dc current, studies were performed on issues such as potential corrosion problems, effect on fish from electric (dc) currents in the sea, and compass deviation [31].

Figure 1a – 12: Landing of a HVDC Cable [31]

1a-3.5 International Projects

Simultaneously with the test operation of the HVDC scheme between the mainland and the island of Gotland in Sweden, the international interest for use of HVDC transmission technology was growing. Already in 1950, the government owned utilities Electricité de France (EdF) and British Electricity Authority (BEA) were investigating conditions for connecting Britain with the continental power system. At this time, the British power system was mainly supplied from fossil fueled based sources while the Franch included several large hydro power stations. Other advantage included the one-hour time difference and the difference in peak power due to e.g., brewing of afternoon tea while industries were still in full operation in Britain while France had a surplus of available generation capacity. It was estimated that an undersea cable between the two systems would, at least, reduce the needed generation capacity with at least 300 MW [34].

During the first half of the 1950s British representatives discussed HVDC know-how with both ASEA and Vattenfall. In April 1954, three weeks into the test operation of the HVDC link to Gotland, Åke Rusck and Uno Lamm attended an Institute of Electrical Engineers (IEE) meeting in London where representatives from BEA and EdF recommended use of ac cables to connect Britain with the continental power system. During the discussions Rusck spoke very positively about the initial operating experiences from the test operation of the HVDC link to Gotland. Initial discussions between ASEA and BEA indicated that BEA would not buy from a foreign manufacturing company and would not, as had been done in Sweden, investigate cost aspects of new technology together with representatives of a manufacturing company [34].

It was not until the spring of 1955 after Rusck had made a presentation on 'High Voltage Transmission in Sweden' at IEE annual banquet and meeting in London that BEA started re-evaluating use of direct current to connect Britain with the continental power system. During continued technical discussions it became clear that the British Admiralty would never allow a monopolar system with single conductor and earth return (via water) since that would result in a few degrees of compass declination, hence a bipolar system with two undersea HVDC cables had to be proposed. In May 1957, BEA and EdF signed a letter of intent to purchase a HVDC system from ASEA [34]. In 1961, English Electric Company UK signed an agreement with ASEA for the design and manufacturing of mercury-arc valves [12], and the first HVDC Cross-Channel scheme (IFA1), a ±100 kV 160 MW HVDC scheme with a 45 km undersea cable, was built by ASEA, and went into service later the same year.

The installation of the Gotland HVDC project also led to much larger international contracts for ASEA such as the 1,440 MW, when initially installed, Pacific-Intertie HVDC project connecting hydro power resources in Oregon (Celilo converter station) to major load centers in southern California (Sylmar converter station) vi a 1,360 km long overhead transmission line, taken in service in 1970. The Pacific-Intertie was undertaken in collaboration between General Electric of the U.S. and ASEA of Sweden, it was first commercial HVDC transmission link installed in the U.S. and the last HVDC project built with the mercury-arc valve technique.

While mercury-arc valves were used for the initial HVDC projects, resources were going towards the development of HVDC converters with thyristors. In May 1967, a thyristor prototype was installed for testing in the Gotland HVDC interconnection and in the spring of 1970 the transfer capacity of this HVDC link was increased by adding a group of thyristor vales at both converter stations [31].

1a-4 Semiconductor Development

1a-4.1 Introduction

Basic characteristics and historic reflections on the development of semiconductor technologies for HVDC applications are discussed below. Although mercury-arc valves are not semiconductors, they are discussed below since they are static converters, i.e., a forerunner to the use of thyristors. The first use of thyristors in a high voltage direct current application was ASEA adding a group of thyristor vales to the converter stations at Gotland HVDC scheme in 1970. The first HVDC scheme completely based on thyristor valves was the Eel River scheme in New Brunswick, Canada, which was built by General Electric (GE) and commissioned in 1972 [38].

Power semiconductors can be classified into three groups based on their controllability [39]:

- Diodes where on and off states are controlled by the power circuit;
- Thyristors which are switched on by a control signal but must be turned off by the power circuit; and
- Controllable switches which can be turned on and off by control signals.

Semiconductor devices have evolved during the decades from low power, signal-level, devices to high power electronics devices. Selection of power semiconductors for a given application is based on factors such as voltage rating, current rating, switching speed, and on state voltage drop. Modern power diodes and transistors are capable of handling voltages and currents in kilovolts and kiloamperes, respectively, with switching times in the order of a few nanoseconds to a few microseconds [40].

1a-4.2 Mercury-Arc Valves

After Thury's early work on dc transmission, based on installing generators and load in series, the converter technology for HVDC schemes became based on valve technology (static converters). The first converter valves were based on mercury-arc valves patented by the American electrical engineer and inventor Peter Cooper Hewitt in 1901 [26]. Mercury-arc valves consist of gas filled tubes where the cathode is a 'pool' of liquid mercury allowing for carrying relatively high currents and the anode consists of a carbon electrode at the top of the tube.

As discussed above, Uno Lamm developed the first commercial HVDC transmission schemes based on mercury-arc valves. The last HVDC scheme with mercury-arc valves was Nelson River in Manitoba, Canada, which was put into service in stages between 1972 and 1977, when the mercury-arc valves were in the 1970s replaced with thyristors for use in HVDC application.

Figure 1a – 13: Gotland HVDC Scheme with thyristor valves in the foreground and mercury-arc valves in the background [37]

1a-4.3 Thyristors

A thyristor is a solid-state four-layer semiconductor device, consisting of alternating P-type and N-type materials (PNPN). The thyristor was developed and patented by GE. The thyristor can control high voltages and current, it is suitable for power applications. Thyristors can, in a simplified way, be considered as controllable diodes, and like diodes, their high voltage and current ratings make them suitable for high power electronics applications [40].

Thyristors are sometimes referred to as silicon controlled rectifiers (SCRs), which is their trade name. The flow of current is blocked when a reverse voltage, negative potential between the anode and cathode, is applied. When a forward voltage, positive potential between the anode and cathode, is applied and the gate terminal is open, the flow of current is blocked and the thyristor is considered to be in a forward-blocking state [40]. By applying a trigger signal to the gate, either a small positive voltage or a light pulse to the gate when the thyristor is in a forward-blocking state with trigger the thyristor into its on (conducting) state.

Consider the case with a diode (replacing a thyristor) in a simple circuit with only the diode and a purely resistive load. The current will start flowing as soon as the positive half-cycle of the input voltage begins and blocked at start of the negative half-cycle of the input voltage. The instant when the current starts to flow in this circuit is referred to as the instant of natural conduction [40]. Replacing the diode with a thyristor allows for introducing a delay (or firing) angle, α, between instant of natural conduction and the start of the conduction, which is triggered by an electric or light pulse applied to the gate. The delay angle (α) is measured with respect to their instant of natural conduction.

Once in the conducting state, the thyristor behaves like a diode with only a small voltage drop, which is in the order of 1 to 2 V, across each thyristor [40]. Early thyristors designs were triggered by an electric pulse applied to the gate, while later thyristor designs were triggered by a light pulse. This light pulse is transmitted through a window in the thyristor casing. Use of a light conductor reduces risk of misfiring due to noise [41].

Under idealized commutating conditions, the valve current becomes a rectangular pulse lasting 120°, with its relative position in relation to the corresponding voltage waveform, is determined by the delay angle. Increasing the delay angle results in a proportionally larger ‘lost’ voltage area, resulting in a reduced average dc-side voltage.

The first thyristor devices were released commercially in 1956 and development of thyristor valves for HVDC began in the late 1960s. As noted above, the first HVDC scheme completely based on thyristor valves, Eel River, was commissioned in 1972 [38]. Other important projects include: The Volgograd-Donbass system, in the former Soviet Union, which was a 720 (or 750) MW HVDC scheme completed in 1965, where the operating voltage of ±400 kV was the highest in the world; The Sardinia–Corsica–Italy (SACOI) interconnection started in 1965 and upgraded in 1988, and then in 1992 with the addition of a third terminal; The 1,362 km long Pacific Intertie built by GE and ASEA, which in 1970 was a 1,440 MW at ±400 kV and in 2004 upgraded by ABB and Siemens to 3,100 MW at ±500 kV; The 1,456 km 1,920 MW Cahora Bassa HVDC system between the Cahora Bassa Dam in Mozambique, and Johannesburg, South Africa completed in 1979, where the operating voltage of ±533 kV was then the highest in the world; The Vyborg back-to-back HVDC scheme with a capacity of 1,070 MW built between 1981 and 1983 (decommissioned in 2022) allowed for exchange of power between the Soviet Union and Finish power systems; The 780 km Itaipu HVDC system in Brazil which commissioned steps between 1984 and 1987 and when the first bipole was completed in 1985 was the world's largest HVDC system by both power (3,150 MW) and voltage (±600 kV); and The 1,514 km Quebec-New England HVDC transmission system, which today is a three-terminal 2,000 MW ±450 kV HVDC scheme operating under a common master control system connecting Raddison (at Hudson Bay) and Nicolet in Canada with Ayer in Massachusetts [26, 42]. This multi-terminal HVDC scheme was originally planned and constructed to become a five terminal system but never operated with more than three terminals.

Figure 1a – 14: Valve Hall in Vyborg HVDC Station (former Soviet Union) [37]

1a-4.4 Insulated-Gate Bipolar Transistors

Insulated-gate bipolar transistors (IGBTs), gate turn-off thyristors (GTOs), and integrated gate-commutated thyristors (IGCTs) have been used in motor drive applications since the 1980s. Higher rated IGBTs, GTOs, and ICGTs allowed for development of voltage source converters (VSCs) for HVDC applications [38]. Most present VSC HVDC schemes are based on modular arrangements of the converters, allowing the IGBTs to operate a relatively low switching frequencies and keeping losses to below 1% per converter station.

The first experimental HVDC scheme with voltage source converters was a 3 MW ±10 kV between Hällsjön and Grängesberg in central Sweden [42], i.e., the same transmission line corridor used by Jonas Wenström for his three-phase ac electric power systems in 1893, started trial operations in 1997. The used VSC technology was based on insulated-gate bipolar transistors developed by ABB under leadership of the Swedish engineer Gunnar Asplund. The first commercial VSC HVDC installation was commissioned in 1999 with an 80 kV, 50 MW, 70 km underground cable to connect onshore wind power (at Näs) to a load center (Visby) on the island of Gotland.

While thyristors have many aspects of an 'ideal' switch for high power applications, they are unable to turn off the device by application with a control signal applied to the gate. Bipolar junction transistors (BJTs) and metal–oxide–semiconductor field-effect transistors (MOSFETs) have characteristics that complement each other. BJTs have low conduction losses in on state but longer switching times while MOSFETs can be turned on and off much faster but their on state losses are larger. Attempts to combine the best qualities of both devices led to the development of the insulated-gate bipolar transistor (IGBT), which today has is the semiconductor of choice for high power electronic applications [39].

There have been several stages of development involving various configurations (designs) for voltage source converters for HVDC applications based on IGBTs. Most installations built until around 2012 were based on variations of 'simpler' pulse-width modulation (PWM), i.e., could be considered an ultra-high-voltage motor drive. More recent installations have been based on variants of a converter topology referred to as a modular multilevel converter (MMC). Multilevel converters produce much less harmonics and have the advantage of allowing harmonic filtering equipment to be reduced or eliminated altogether. The VSC technology has today captured a significant portion of the HVDC market [38].

HVDC voltage source converters schemes based on IGBTs have since been built and installed at multiple locations world-wide [42]. In 2000, at least two commercial VSC HVDC systems were installed. They were: The Directlink (Terranora) Interconnector in New South Wales, Australia, which is a ±80 kV 180 MW 63 km link for trading of electricity between New South Wales and Queensland and the Eagle Pass back-to-back 36 MW HVDC scheme at Rio Grande in Texas for power exchange between Texas and Mexico. The first non-back-to-back VSC HVDC scheme in the United States was the Cross Sound Cable, which is a ±150 kV, 330 MW 40 km bipolar submarine dc cable between New Haven in Connecticut and Shoreham, on Long Island, New York. The project started in 2002 and received an initial emergency permit to operate after black-out in the eastern US on August 14, 2003. The first VSC HVDC project using MMC technology was the Trans Bay scheme in San Francisco, California.

1a-5 Why HVDC?

1a-5.1 Background

It could be noted that the development of high voltage direct current transmission started several decades before the first commercial HVDC system was ordered. One key aspect of the success of the early development of HVDC transmission was the development of the markets for the novel HVDC technology and its applications in parallel with the product development, creating a positive technology-friendly environment. It should also be pointed out that it was acknowledged that "it will cost more than expected and take more time, but the market is a lot bigger than we first thought," which created such a positive, technology-friendly environment [28].

As noted in the previous section, initial attempts were made already before the development of semiconductors, which can be said to have started with when Bell Laboratories introduced the transistor in 1947. There was a rapid development of semiconductors for various applications, including HVDC, during the second half of the 20th century. Today HVDC technology is again experiencing a golden age, thanks to continued development of semiconductors and driven by the expansion of renewable energy, where over 90% of total power expansion globally in 2024 came from renewable energy resources [43].

1a-5.2 Characteristics of HVDC

While converter stations cost more than ac substations, for longer transmission lines and medium length cables, HVDC becomes a more economical alternative than equivalent AC transmission and in general, the longer the route length the more competitive HVDC becomes. This results in that more renewable energy can be transported over long distances without significant loss of power. HVDC thereby offers several advantages, making it an ideal solution for interregional transmission by providing efficient long-distance transmission capability and for integrating renewable energy sources. HVDC further allows for interconnection of non-synchronous power systems and ability to control flow of power across the interconnection.

In a bipolar configuration, the HVDC scheme only requires two conductors while the HVAC alternative requires three conductors. While longer ac cables require reactive power compensation mid-point, this is not required for dc cables. HVDC lines also have lower transmission losses compared to HVAC lines. HVDC schemes can also be designed to provide active power compensation during ac system disturbances thanks to fast and flexible control systems.

Characteristics of HVDC Transmission be separated into:

- Controllable - Power injected where needed
- Facilitates integration of remote diverse resources with less impact on existing grid
- Higher power capacity rating with fewer lines
- Less expensive lines
- No stability distance limitation
- Long cables, shared ROW with no common failure mode
- Reactive power demand limited to terminals independent of distance
- Lower losses
- No limit to underground or sea cable length
- Asynchronous, ‘firewall’ against cascading outages

1a-5.3 AC vs. DC Considerations

Rationales for selecting HVDC schemes over ‘traditional’ ac transmission alternatives can include both economic and technical considerations. Some technical considerations include long-distance transmission of large quantities of electric power between ac electric systems, need for long transmission cables (e.g., water crossings or in dense urban areas), and interconnection of non-synchronously operated ac power systems. HVDC schemes can by being able to control and modulate the power flow (in either direction) between two interconnected ac grids or within a synchronously operated grid, also support power system operation by providing stabilization of ac power systems and e.g., reduce risk of cascading failures [44].

Maximum power of a HVDC scheme is determined by voltage determined by the number of series connected semiconductor devices and their current handling capacity. The rated power is for a two terminal HVDC scheme often determined by the rating of the transmission conductor (overhead line or cable). In a back-to-back link, there are no such external requirements, and it is possible to optimally use the full current carrying capability of the thyristors. This results in back-to-back HVDC schemes generally operating with lower dc voltages and higher currents than comparable long-distance HVDC transmission schemes.

Among the options for increasing the transfer capacity of existing HVAC lines or maximizing utilization of an existing right-of-way, such as re-conductoring of increasing the operational voltage of a line, HVDC is generally considered the HVDC is generally considered the most effective way of gaining major increases in transfer capability. Since HVDC allows for transfer of larger power over longer distances than HVAC, conversion of existing ac transmission lines to dc operation provides can provide great value. Possibilities and constraints associated with conversion of transmission lines from ac to dc operation is e.g., discussed in CIGRE Technical Brochures 425 'Increasing Capacity of Overhead Transmission Lines – Needs and Needs and Solutions' and 583 'Guide to the Conversion of Existing AC Lines to DC Operation' [45, 46].

While building converter stations at each end of a HVDC link involves considerable costs, and are more expensive than comparable HVAC substations, the overhead line or cable costs less and the losses are lower. Hence, there is a break-even distance, which depends on factors such as use of overhead lines or cables, where the HVDC link will become the least expensive alternative.

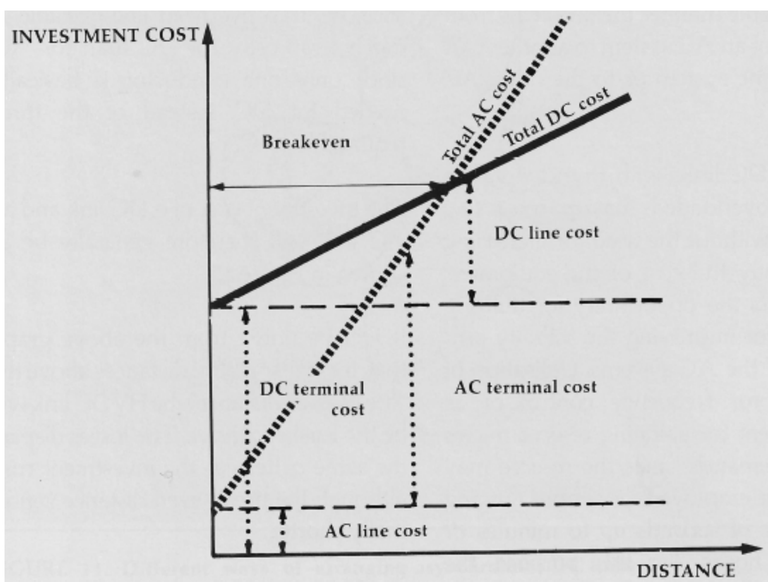

Figure 1a – 15: Investment Cost as Function of Distance for HVAC and HVDC Links [37]

Conversion of stability limited HVAC transmission lines or HVAC transmission corridors restricted by existing right-of-way issues to HVDC operation could be an efficient solution to provide increased transmission capacity with use of an existing right-of-way. Conversion of ac lines to dc operation could also, as later briefly discussed under ‘Control and Protection Systems’ in the section on Major Equipment Categories, be used to improve damping of electromechanical oscillations. Another example where HVDC schemes can play an important role, both in technical and economic terms, is the connection of large-scale introduction of renewable energy sources such as offshore wind power. Apart from economic advantages, HVDC can hence provide improved control of power flow as well as enhanced stability and reliability of ac power systems.

Although HVDC also has some disadvantages, such as its integration within an ac power system has to be carefully considered and its cost can be higher than an equivalent ac solution, advantages of HVDC include interconnection of asynchronous ac power systems, providing large transfer capability over long distances, allowing for use of long-distance transmission with cables, and ability to improve ac system stability [47]. Another benefit from the use of HVDC is that it allows system operators control of the flow across the HVDC line which can allow relieve congestion in a parallel ac transmission system. Use of HVDC also reduces the requirements and impacts the available land through where a transmission link is routed.

1a-6 HVDC Topologies

1a-6.1 Monopolar vs. Bipolar HVDC schemes

HVDC transmission schemes can be constructed based on number of dc-side topologies, depending on several factors such as technical, economic, redundancy, availability, and environmental impact, and required transmission capacity, which often are in competition with each other aspects. The decision on the most suitable dc-side topology is strongly dependent on specific project requirements [48]. This section presents some basic properties of monopolar and bipolar HVDC schemes.

The presentation below of basic aspects of monopolar (one dc line) and bipolar (two dc lines) HVDC schemes focuses on point-to-point connections, i.e., HVDC schemes with two converter stations. Additional guidance and considerations of commonly used dc-side topologies are provided in Section 7a ‘Electrical configurations for LCC PTP systems’ of Module 7a ‘Point to point HVDC systems.’ While bipolar system allows for higher power transfer capabilities, they cost more since they require additional valves and additional high voltage lines compared with monopolar HVDC schemes.

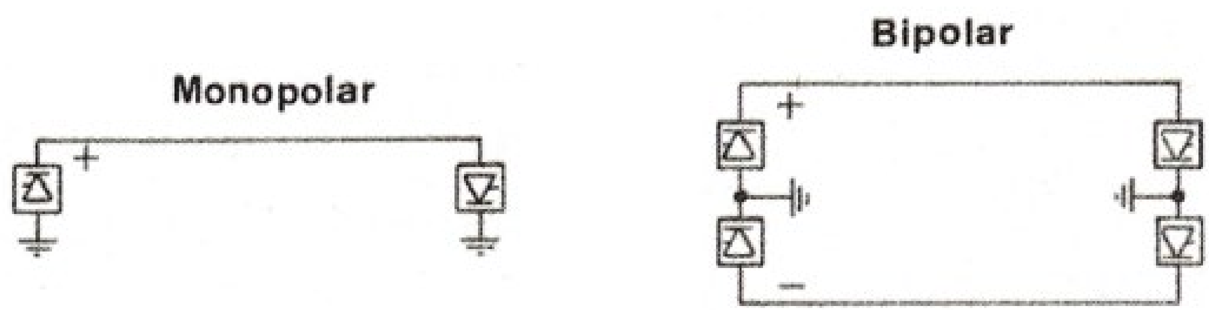

Figure 1a – 16: Transmission Modes: Monopolar vs. Bipolar [37]

Monopolar configurations are based on one high voltage line (overhead line and/or cable) between the converter stations and dc current returning earth, either via earth electrodes or a metallic return conductor. Since the earth or metallic return is at ground potential and only the conductor is at (plus or minus) the transmission voltage, such dc configurations are referred to as asymmetric HVDC schemes. While a monopolar HVDC scheme can be a first step, later to be expanded into a bipolar configuration, it could be noted that use of earth electrodes is becoming less common due to environmental considerations. If the line is out of service or subject to a sustained fault, a monopolar HVDC scheme is not able to transfer power which results in lower availability than for a bipolar configuration.

Each phase on the ac-side in a 12-pulse LCC HVDC converter is connected to the converter valves via a Y/Y connected transformer winding and a Y/Δ connected transformer winding. The most common way of arranging the thyristor valves in 12-pulse converter is with three such valve 'towers' (one for each phase on the ac-side) per pole. This combination of two six-pulse groups of thyristor valves connected into series is often referred to as a quadruple valve.

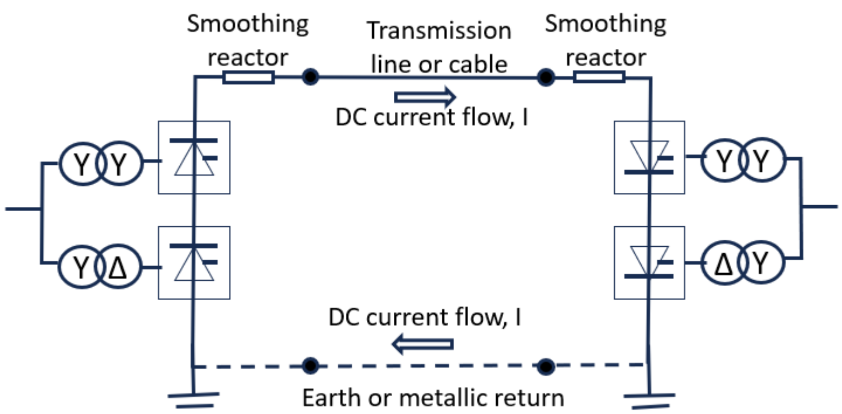

Figure 1a – 17: Electrical Configurations for Asymmetric Monopole [49]

Bipolar HVDC topologies refer to a HVDC scheme with two separate high voltage lines between the converter terminals, with or without earth return via earth electrodes or a metallic return conductor. The two high voltage lines are normally connected at opposite polarities, one with positive and the other with negative polarity to ground. Under normal operation of a bipolar HVDC schemes with a metallic return conductor is that when both poles are in operation, the imbalance current flowing in the ground path is very low.

In case one pole or one high voltage line experience a permanent fault in a HVDC scheme with earth return, the system can continue to operate in monopolar mode, probably with a reduced power transfer capability, utilizing one high voltage line and current return flow via the earth electrodes or metallic return conductor. As noted above, the use of earth electrodes resulting in ground return current can have environmental impacts and may not be allowed. Hence, the use of a metallic conductor for earth return is becoming more common. It may also be possible to use one of the high voltage conductors as earth return path to allow for monopolar operation during single pole operation [48].

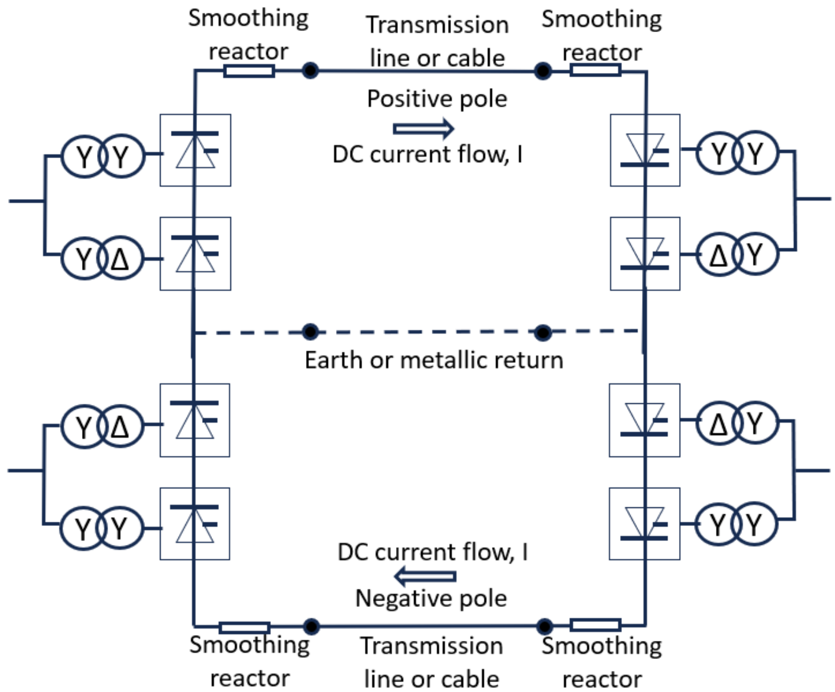

Figure 1a – 18: Electrical Configurations for Symmetric Bipole [49]

A less common type of HVDC topology is the homopolar HVDC scheme which comprises of two (or more) high voltage lines connected such that they have the same polarity with respect to ground. Homopolar HVDC schemes can be configured by 'inverting' half of each quadruple valve such that current in both dc conductors are e.g., negative with respect to ground [50].

1a-6.2 Back-to-Back HVDC

Back-to-back HVDC schemes can be used to provide 'bridges' between non-synchronous ac power systems. There are five, two major and three minor, non-synchronously operated ac power systems (a.k.a. Interconnections) in North America. The two major are the Eastern and Western Interconnections, and the three minor are Quebec, Texas, and Alaska [51]. There are several back-to-back HVDC converters in operation in between the asynchronous Interconnections in North America. An example is the Châteauguay HVDC station near Montreal in Quebec, which is a 1,000 MW back-to-back interconnection between Hydro-Québec and New York Power Authority (NYPA) constructed in 1984 [52].

1a-6.3 LCC vs. VSC Technology

Today's HVDC schemes use power electronics to convert alternating (ac) current to direct current (dc) and then back to ac. HVDC converters are almost always bi-directional, i.e., they can convert from ac to dc or from dc to ac. HVDC converters can e.g., be used to transmit electricity over long distances, or to connect AC power systems with different frequencies. The device that transforms ac to dc or vice versa is called a converter. The converter that converts the alternating current to direc1t current, i.e., rectifying the current, is referred to as the rectifier. The converter that converts the direct current to alternating current is referred to as the inverter.

This section will introduce and discuss some differences between power electronics-based line commutated converters (LCCs) and voltage source converters (VSCs). While LCCs are constructed with power electronic switches that can only be turned on, VSCs are constructed with power electronic switches that can be turned both on and off. In general, VSC systems are faster at responding to changes in system conditions than LCC systems.

In LCC systems, which are also referred to as current source converters, the current in the dc-link cannot change instantaneously because of inductances in the dc circuit. In a modern LCC system, each converter consists of number of thyristors. In VSC systems, there is a capacitor on the dc-side in parallel with the converter, and these systems are thus referred to as voltage source (or voltage-link) converters [53]. Adjusting power flows on an HVDC link requires the intervention of the operator or control system.

An important difference between current source converters and voltage source converters is the absence of commutation overlap, which makes VSC operation more predictable and easier to analyze. In a line commutated converter, a short-circuit in the ac system in proximity to the inverter terminal can cause a commutation failure, resulting in a temporary interruption of the power transfer. Voltage source converters do not experience commutation failures and can hence continue to transfer power during such faults in the ac system, although reduced based on the available ac voltage during the period until the fault is cleared.

HVDC schemes with line commutated converters allow for higher power conversion capacities with lower losses than those with voltage source converters. LCC also allows for short-term overloading, which may be an advantage during power supply disturbances. The total operating losses for a LCC HVDC scheme are typically between 0.7% and 0.8% of the scheme's ratings [54], which is less than for a HVDC VSC scheme.

Other differences between LCC and VSC include that voltage source converters are protected from dc-side line voltage transients by the dc capacitors. Since the harmonic currents drawn from the ac system are a function of the transformer leakage reactance, which increases rapidly for higher frequencies, this greatly reduces higher order harmonics in VSC HVDC schemes [55]. Finally, line commutated converters have lower losses than voltage source converters, in particular if the VSC HVDC scheme uses pulse width modulation (PWM).

1a-7 Line Commutated Converters

This section describes basic properties of line commutated converters, such as waveforms and harmonics. Since the majority of HVDC Schemes in North America presently are based on line commutated converter (LCC) technology, this section will go into more depth than the following section which describes basic properties of voltage source converters (VSC). While specifically referring to LCC designs with thyristors, many of the considerations are the same for VSC since both are based on switchable semiconductors.

1a-7.1 Waveforms

The fundamental building block in a line commutated converter HVDC system is a simple six-pulse converter, which is a three-phase full-bridge converter with six thyristors. This three-phase full-bridge thyristor converter consists of two thyristors in each of three phase legs.

The six-pulse voltage waveform is established by firing the thyristors in a specific sequence. Assuming the thyristors start conducting at the instant when the current would begin to flow if it were a diode, this would correspond to a firing of the thyristors when the delay angle (α) is 0° which also is referred to as the instant of natural commutation. Let's start the sequence when phase a is the highest and phase b the lowest of the three-phase ac voltage magnitudes, i.e., when thyristors 1 and 6 are conducting. Next, the voltage in phase b would become the lowest and the current commutates from thyristor 6 to thyristor 2, i.e., thyristors 1 and 2 are now conducting. This is followed by the voltage in phase b becoming the highest, i.e., thyristors 3 and 2 are conducting. The sequence would continue with the following pairs of thyristors conducting: 3 and 4, followed by 3 and 4, then 5 and 4, then 5 and 6, and back to 1 and 6. Both thyristors in the same leg, e.g., 1 and 4 should be conducting at the same time since this would correspond to a short-circuit between the positive and negative sides on the dc-side of the valve.

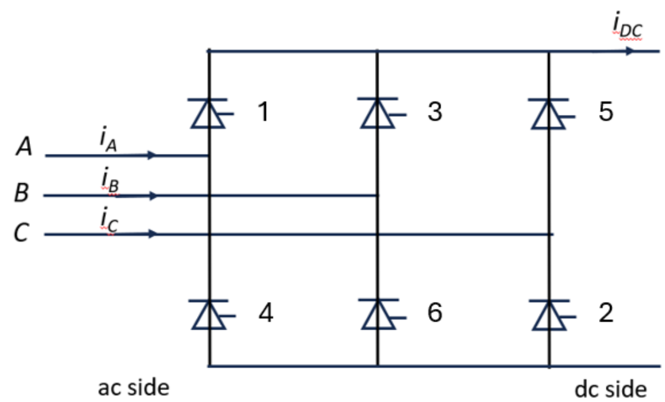

Figure 1a – 19: Six-Pulse Line Commutated Converter

To derive a formula for the dc link voltage, V_d, it is initially assumed that six-pulse converter is supplied by an infinite symmetrical (ideal) three-phase ac voltage source. Further, in the first formulation for the dc link voltage, it is assumed the thyristors operate with a 0° delay angle, i.e., they could for this initial derivation be replaced by diodes. During each time instance one upper (# 1, 3, 5) thyristor and one lower (# 2, 4, 6) thyristor is conducting. The thyristor with the highest phase voltage in the upper group is conducting while the remaining two thyristors in the upper group become reverse biased. In a similar way, the thyristor with the lowest phase voltage in the upper group is conducting while the remaining two thyristors in the upper group become reverse biased. The dc voltage can be written as

$$v_d(t) = v_{Pn}(t) - v_{Nn}(t)$$

where P and N represent dc voltages with respect to the source neutral at the upper and lower converter terminals, respectively. The plots below show voltages for a three-phase six-pulse converter, with a Y-to-Y connected transformer, and the corresponding six-pulse dc voltage. The voltages are plotted in per unit (p.u.) and the scale on the time axis is in electrical degrees.

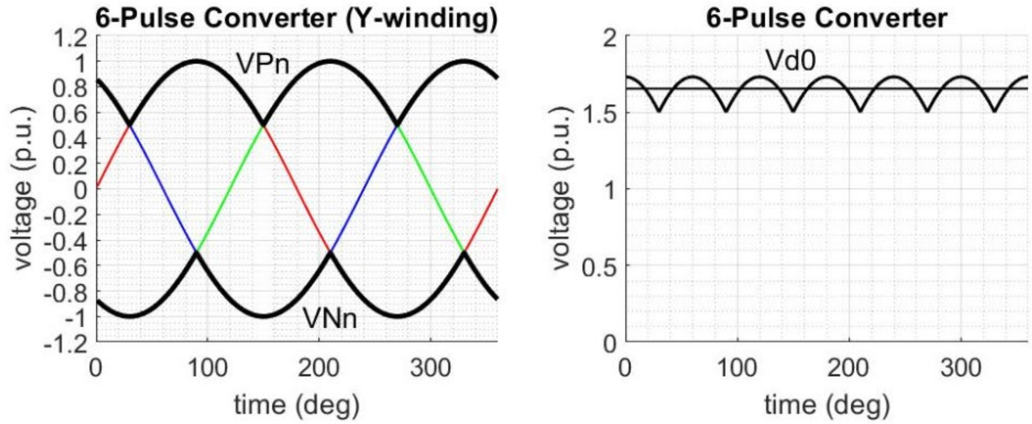

Figure 1a – 20: Three-Phase Six-Pulse Line Commutated Converter

The average voltage on the dc-side can, based on the assumption that the thyristors operate with a 0° delay angle, i.e., replaced by diodes, can be calculated by considering a 60° (π/3 rad) interval of the waveform. Since each voltage maximum is set 60°, there are six such pulses per period, hence the name six-pulse converter. With the peak value of the input ac voltage source being $\sqrt{2}\, V_{LL}$, where subscript LL denotes that this is a line-to-line voltage[1], the average dc-side voltage can be calculated as

$$V_{d0} = \frac{1}{\pi/3} \int_{-\pi/6}^{\pi/6} \sqrt{2}\ V_{LL} \cos\omega t \; d(\omega t) = \frac{3\sqrt{2}}{\pi}\ V_{LL}$$

where the angular frequence is $\omega = 2\pi f$ and the subscript 0 refers to the 0° delay angle.

While the current always starts to flow when a (positive) forward voltage occurs across the diode, the thyristor can block the forward voltage such that the thyristor starts conducting later by adjusting the delay angle α of the thyristor to a number between 0° and 180°. The delay angle α is calculated in electrical angle degrees from the point-in-time when the voltage across the thyristor, where the anode is positive and the cathode is negative, to the point-in-time when the pulse is applied to the gate of the thyristor. Once the thyristor has been triggered to conduct by the pulse applied to the gate, the thyristor will start conducting current with a small voltage drop, which for this initial derivation can be ignored.

Introducing the delay angle α, which is measured with respect to the instance of natural conduction, i.e., when current was going to start flowing through the semiconductor device if the thyristor was considered to operate as a diode, reduces the average voltage on the dc-side.

Thyristors operating with a delay angle α, delaying the gate pulses by α every π/3 radian, results in a voltage 'loss,' which can be expressed as [53]

$$\Delta V_\alpha = \frac{1}{\pi/3} \int_{0}^{\alpha} \sqrt{2}\ V_{LL} \sin\omega t \; d(\omega t) = \frac{3\sqrt{2}}{\pi}\ V_{LL}\,(1 - \cos\alpha)$$

The average voltage on the dc-side can then be calculated as

[1] The line-to-line voltage is $\sqrt{3}$ times the line-to-neutral voltage in a symmetrical three-phase system.

$$V_{d\alpha} = V_{d0} - \Delta V_{\alpha} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha$$

Since the inductances Ls were neglected in the above idealized case, the ac-side current commutates from one thyristor to the next without any delay. Including effects of ac-side line inductances results in an additional voltage drop which can be expressed as [53]

$$\Delta V_u = \frac{1}{\pi/3} \omega L_S I_d$$

where the subscript u refers to the electrical angle during which a pair of thyristor valves are commuting, i.e., the commutation interval which sometimes is referred to as the 'overlap' angle, and Id refers to the dc-side current. The resulting average voltage on the dc-side can now be calculated as

$$V_d = V_{d\alpha} - \Delta V_u$$

which, depending on if adding or subtracting the above additional voltage drop due to inclusion of the inductances Ls be written as

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha - \frac{3}{\pi} V_{LL} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos(\alpha + u) + \frac{3}{\pi} V_{LL}$$

Noting that voltage maximum is set 60° apart for the above six-pulse converter and the shift in voltage angles between wye-wye and wye-delta transformers are 30° it is possible to combine, by series connection of a six-pulse converter fed by a wye connected transformers winding and a six-pulse converter fed by a delta connected transformers winding, to obtain a 12-pulse converter, which is standard in today's LCC HVDC systems.

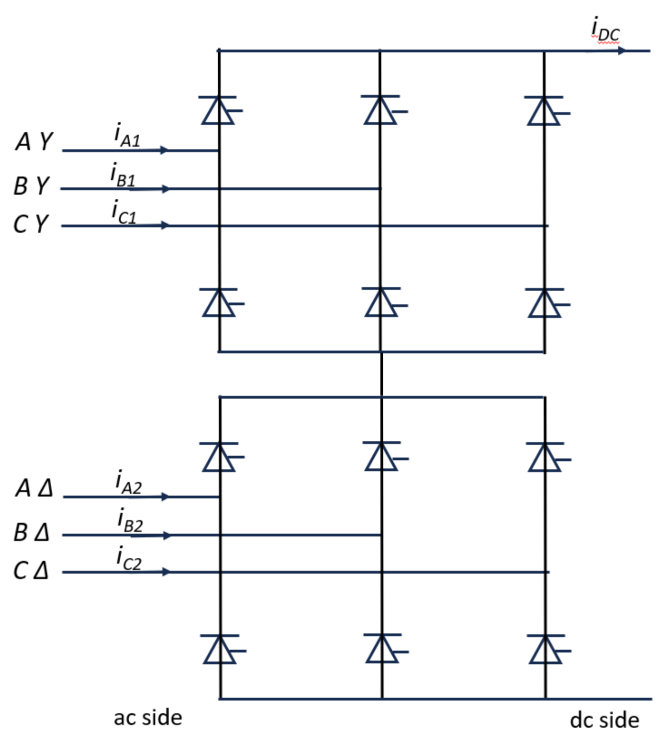

Figure 1a – 21: 12-Pulse Line Commutated Converter

The 12-pulse converter reduces the amount of necessary harmonic filtering by eliminating the need for fifth and seventh tuned filters. The plots below are proving voltages for the delta-winding, i.e., with a 30 degrees phase shift from the Y-winding and the corresponding 12-pulse dc voltage. The voltages are plotted in per unit (p.u.) and the scale on the time axis is in electrical degrees.

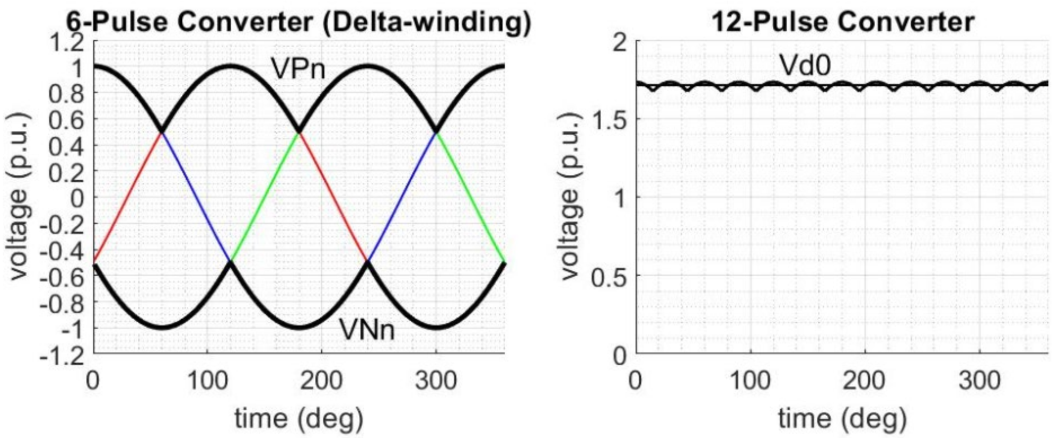

Figure 1a – 22: Three-Phase 12-Pulse Line Commutated Converter

1a-7.2 AC-Side Harmonics

The number of pulses, e.g., in a six-pulse or 12-pulse converters, is directly proportional to the order of harmonics. HVDC converters provide a source for current harmonics on the ac-side and voltage harmonics on the dc-side [55]. Excessive harmonic levels should be avoided since they can result in voltage distortion, additional losses, overheating of e.g., capacitor banks, and harmonic interference with e.g., communication systems. Hence, ac filter banks are installed on the ac-side of HVDC converters to decrease the harmonic distortion of the ac-side current and voltage to acceptably low levels.

Modern LCC HVDC converters consist of 12-pulse converter valves consisting of two six-pulse converters, where one six-pulse converter group is connected to a Y/Y transformer winding and the other six-pulse converter group is connected to a Y/Δ transformer winding. The total ac-side current of a 12-pulse LCC converter is the sum of the two six-pulse converters.

Currents flowing on the ac-side via the ac-side windings of the converter transformers have a sinusoidal fundamental component but are non-sinusoidal since they are based on rectangular shaped currents for the Y/Y Δ six-pulse converter and a more 'triangular' (stepped) shaped current for the Y/Δ six-pulse converter. The Y/Y and Y/Δ six-pulse converters are then combined into a 12-pulse converter. The described ac-side currents correspond to the ac-side current under 'ideal' conditions, i.e., with no commutation overlap, ripple-free direct current, balanced purely sinusoidal commutation voltages, and equally spaced converter firing pulses [55].

The ac-side currents can be expressed as via Fourier series analysis, where ω is the is the angular frequence, in a 60 Hz system $\omega = 2\pi 60$, and Id is the dc-side current, as [55]

$$i(t) = \frac{2\sqrt{3}}{\pi} I_d \left(\sin \omega t + \frac{1}{5} \sin 5\omega t + \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega + \cdots \right)$$

for a Y/Y six-pulse converter transformer, and

$$i(t) = \frac{2\sqrt{3}}{\pi} I_d \left(\sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega - \cdots \right)$$

for a Y/Δ six-pulse converter transformer.

There are no even harmonics in the above expressions for the ac-side current, i.e., the above Fourier series only contains sines, since the ac-side currents are off functions where the two current pulses are of equal size but opposite polarity during each cycle, i.e., $f(-x) = -f(x)$. There are neither any third nor multiples of third harmonics (3n) since the current pulse is one third of each 60 Hz cycle, so the remaining current harmonics in the six-pulse converter transformers are on order of $6n \pm 1$, where n is an integer, i.e., 5, 7, 11, 13, etc.

The 12-pulse converter which is one six-pulse converter group connected to a Y/Y transformer winding and one six-pulse converter group connected to a Y/Δ transformer winding connected in series hence eliminates the 5th and 7th as well as 17th and 19th harmonics, etc. The ac-side currents in a 12-pulse LCC converter transformer hence becomes

$$i(t) = \frac{2\sqrt{3}}{\pi} 2\, I_d \left(\sin \omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega + \frac{1}{23} \sin 23\omega t + \frac{1}{25} \sin 25\omega t + \ldots \right)$$

Hence, the remaining current harmonics on the ac-side of a 12-pulse converter transformer are on order of $12n \pm 1$, i.e., 11, 13, 23, 25, etc. The amplitude of these current harmonics flowing in the ac-system decrease with increasing order, i.e., the hth order harmonic has an amplitude that is 1/h times the amplitude of the fundamental harmonic.

1a-7.3 DC-Side Harmonics

The main purpose of dc-side filtering in HVDC transmission systems is to prevent external induced interference with nearby communication systems, especially if these are using metallic lines. Problems with communication system were a very important problem to solve during early development of HVDC transmission, while conversion to optical fiber and microwave technologies have significantly reduced these interference problems. Voltage source converters emit considerably lower magnitudes of dc-side harmonics than line commutated converters. Most present VSC schemes also use shielded underground cables, which further reduces the range of any potential external interference [56].

LCC HVDC converters act as voltage harmonic source on the dc-side. An idealized voltage source connected across an unloaded six-pulse converter results in of 6n, where n is an integer, i.e., 6, 12, 18, 24, etc. voltage harmonics on the dc-side and an unloaded 12-pulse converter results in of 12n, i.e., 12, 24, 36, etc. voltage harmonics on the dc-side. Similar as on the ac-side, tuned as well as high-pass filters can be used to mitigate and reduce harmonics to be within acceptable ranges.

HVDC schemes based on VSC technology allow for additional flexibility due to the ability to switch the used IGBTs on and off many times per cycle which improvs the harmonic performance. Presently installed VSC HVDC schemes are commonly built as modular multilevel converter

(MMC) which can be operated with very low levels of harmonic distortion. Voltage source converters generally shift the harmonic spectrum to higher frequencies than with line commutated converters, as discussed above. The dominant harmonic frequencies for VSC are sidebands of the PWM frequency and multiples thereof. These higher harmonic frequencies usually allow filter equipment to be (much) smaller [38].

1a-7.4 Short-Circuit Requirements

HVDC converters require a certain level of short-circuit capacity in the interconnected ac transmission system to function properly. The level of required short-circuit strength of the interconnected system depends on the type of converter technology, e.g., VSC technology can connect to lower short-circuit strength ac systems than LCC technology. There are several aspects to consider related to short-circuit capacity requirements in LCC HVDC systems.

The lower limit of short-circuit capacity for LCC converters is related to temporary overvoltages during load reduction. The problem is normally related to the inverter terminal since the rectifier terminal is where power is extracted into the HVDC scheme. Since power is taken from an ac system or synchronous generator at the rectifier terminal the short-circuit capacity there should, at least in most cases, be sufficient.

It is partly an economic design problem since high load rejection overvoltages result in high arrester voltages and consequently high insulation levels and higher cost for the inverter converter terminal equipment. High load rejection overvoltages, indicating that the ac network is weak, could be addressed by e.g., installing synchronous condensers [31].

Overvoltages as well as normal (operating) voltages must be considered when dimensioning HVDC transmission. Due to the somewhat lower overvoltage factor, the required clearance distances between conductor and structure or between conductor and ground are lower for dc than ac. Further, due to the higher power transfer capability per transmission tower, HVDC allows for more narrow rights-of-way than ac transmission lines for the same power transfer capability. It can be noted that HVDC transmission with underground cables results in no visible rights-of-way.

1a-8 Voltage Source Converters

1a-8.1 Introduction

Voltage source converters have, as described in the historic exposé on HVDC technology above, been used in HVDC transmission systems since 1997. Insulated gate bipolar transistors (IGBTs) together with gate turn-off thyristors (GTOs) and integrated gate-commutated thyristors (IGCTs) belong to a category of semiconductor devices referred to as self-commutating, meaning that these converters can be commutated on or off independently of the load current, i.e., they are not dependent on the ac system voltage for its correct operation.

Voltage source converters are based on self-commutated converters, conventionally IGBTs, to connect HVAC and HVDC systems. Self-commutated converters are capable of self-commutation, i.e., being able to generate ac voltages without the need to rely on an ac system, which allows for independent rapid control of both active and reactive power and black start capability [54]. Voltage source converters can be classified with respect to the used converter topology, which started with two-level VSCs, going to three-level VSCs, and evolving into modular multilevel converters (MMCs), which can be further differentiated into half-bridge and full-bridge converters.

Present VSC technology seems to favor the use of IGBT semiconductors in modular multi-level converter configuration, constructed by cascading individual converter 'blocks.' Voltage source converters can also use pulse-width modulation (PWM) high-frequency switching to establish the desired fundamental and harmonic voltage waveforms by modulating the width of the voltage pulses. PWM based MMCs could be used to generate the desired sinusoidal voltage waveform and improve the quality of the transmitted power by reducing harmonic distortion. To achieve this, the PWM switching frequency should be several times the fundamental frequency, which results in increased losses.

A shortcoming of LCC HVDC schemes compared with VSC HVDC schemes is the dependence of line commutated converters on a relatively strong ac-side system to provide adequate commutation voltages. Another shortcoming of line commutated converters is the large reactive power requirements, which together with injection of 'lower' order harmonics (e.g., 11^{th} and 13^{th}) requires installation of large volumes of harmonic filters and shunt capacitor banks, resulting in a large ac-side switchyard. The footprint of a VSC converter station is hence considerably smaller than of a LCC based converter station, as there is less or even no need for reactive compensation equipment at a VSC based converter station.

Unlike in current-link (LCC) systems, in voltage-link (VSC) systems, there is a capacitor on the dc-side of the converter in parallel that appears as a voltage port and hence the name voltage source converters. Since change of power flow direction is achieved by reversing direction of the current, VSCs systems can faster and more easily allow for power reversals than LLCs. where polarity reversal must take place to change the direction of power flow [42]. Hence, VSCs can more easily, than LCCs, be integrated into multi-terminal HVDC schemes.

1a-8.2 Operating Principles

Voltage source converters allow for self-commutating conversion by use of advanced switching devices, such as IBGTs, which have both turn-on and tune-off capability. To provide a basic insight into operation of a VSC, assume converter valves are lossless, dc capacitor ripple is negligible, and converter transformers are lossless. In case of a two-level VSC converter where the ac terminals are switched between two discrete levels ($+V_d/2$ and $-V_d/2$) [55].

Since the conduction in semiconductor switches is unidirectional, anti-parallel diodes are connected across the semiconductor switches so that current can flow in both directions. When the two main switching devices are blocked, the two anti-parallel diodes form an uncontrolled rectifier, which allows the external ac voltage to charge the dc capacitors. Once the dc capacitors are charged, the voltage source converter can commence operation. By turning on and off the main switches in a desired pattern, a VSC can operate in all four quadrants, i.e., positive or negative active power, and positive or negative reactive power. The VSC can, at fundamental frequency, be represented by a voltage phasor, with voltage magnitude and phase angle determined by the dc voltage and the firing pulse pattern [55].

When the VSC is connected between two ac networks, it can control active power flow across the HVDC interface and reactive power injections, either leading or lagging, at each terminal. Under the discussed ideal conditions, the three phase power from the VSC terminal matches the power on the dc-side, i.e.,

$$P = V_d I_d = \sqrt{3}\, V_{LL}\, I_L \cos\phi$$

where V_{LL} is the line-to-line voltage on the ac-side, I_L is the current on the ac-side, and ϕ is the power factor angle between the phase voltages and phase currents on the ac-side of the converter. In addition to active power, the VSC can under discussed idealized conditions supply (leading or lagging) reactive power to the ac-side in accordance with the following formula.

$$Q = \sqrt{3}\, V_{LL}\, I_L \sin\phi$$

The reactive power can hence, within the capability of the converter, be controlled in magnitude, absorbed or supplied, by the VSC [53]. Maximum allowable valve current and maximum allowable dc voltage determines limits for how much active and reactive power a VSC can deliver. The active and reactive power limits can be represented in a PQ-diagram, similar as the capability curve of a synchronous generator.

Without the dc cable line being in-service, the voltage source converters on each side of the dc transmission link can, if available, act as Static Synchronous Compensators (STATCOMs). A STATCOM can be thought of as a fast-acting ideal rotating synchronous compensator, i.e., shunt-connected device used to regulate voltage and provide reactive power compensation in a power grid, thereby improving grid stability and power quality.

1a-8.3 VSC Applications

Voltage source converter HVDC schemes are very well suited for interconnection of remote generating facilities such as offshore wind (OSW) farms. Most VSC HVDC applications are built with cable connections, which are advantageous if the OSW farm is located a distance away from the onshore interconnection point. Use of VSC technology supports the development of multi-terminal HVDC network (MTDCN) applications and can provide power system support in forms of black-start capability, fast reactive power support, and voltage control. The following two sections provide examples of applications of VSC HVDC technology.

1a-8.3.1 Atlantic Offshore Wind

HVDC can provide great value for onshore area interconnection, and offshore interconnections of large-scale wind farms as well as both onshore and offshore multi-terminal HVDC grids. In the US, several infrastructure projects, combining both offshore wind export and interconnection functionality were discussed and announced in 2023 [57]. Several of these projects would require multi-terminal HVDC technology and all converter tenders are based on VSC technology. Some European grid operators discuss the role of multi-terminal VSC HVDC overlay grids as the bulk electrical energy carrier of choice.

In accordance with the above referenced DNV report [57], there were at least 46 HVDC projects to be installed over the next decade, equating to a 94,3 GW addition of HVDC transmission capacity, and at least 18,000 km of HVDC cable, announced and/or awarded in 2023. After being part of pioneering many aspects of HVDC technology, the U.S has during the last decades experienced a slowdown in newly-built HVDC transmission capacity, often due to regulatory, permitting and policy hurdles as well as financing challenges [57].

A comprehensive approach for analysis of offshore wind transmission expansion planning is provided in the report ‘Offshore Wind Transmission Expansion Planning for the U.S. Atlantic Coast’ [58]. The objective of the models, methods, and processes developed for evaluating developed for OSW transmission expansion planning on the U.S. Atlantic Coast was to develop a tool allowing for quick and accurate ‘round-trip’ conversations between planners and decision-makers about transmission expansion and power systems analyses.

An action plan for use of HVDC to develop an offshore transmission grid in the U.S. Atlantic region is discussed is presented in a report by the U.S. Department of Energy (DOE) and the Bureau of Ocean Energy Management (BOEM) [59]. Options reviewed include development of inter-regional multi-terminal VSC HVDC transmission lines. Critical path items for such a development include standardization of requirements for HVDC technology. Another report is the Atlantic Offshore Wind Transmission Study by the National Renewable Energy Laboratory (NREL) and the Pacific Northwest National Laboratory (PNNL) [60]. This report identifies and evaluates pathways to enable offshore wind energy deployment in the Atlantic Ocean through coordinated development of offshore transmission solutions.

In January 2023, the six New England states filed a JSIP (Joint Statistical Innovation Project) Concept Paper ‘Joint State Innovation Partnership for Offshore Wind’ with the Grid Deployment Office at DOE [61]. The Concept Paper, which proposed to explore a solicitation process to seek a modular development structure to facilitate the initial deployment of offshore HVDC systems in the near term while enabling upscaling of the system to accommodate a first-in-the-nation networked or ‘meshed’ multi-terminal high voltage direct current (MTDC) system as that technology becomes available, was approved by DOE in March 2023. A fully networked MTDC system would provide greater reliability and resiliency benefits and improve regional (and eventually interregional), capacity transfers and set the path for the possibility of an innovative offshore backbone system along the Atlantic coast.

1a-8.3.2 TenneT

An example of grid connection of large-scale offshore wind power to the shore is taking place in the North Sea as part of the European energy transition as part of the objective of making Europe a climate-neutral continent by 2050. TenneT, the utility for the Netherlands and large parts of Germany, plans to connect 14 VSC HVDC offshore grid connection systems with a transmission capacity of 2 GW each in the North Sea by 2032 – seven in Germany and seven in the Netherlands. The objective of the program is to contribute to national as well as European climate goals, by efficient offshore wind connections that minimize the environmental impact. The VSC connections are based on a standardized ‘one-size-fits-all’ 2 GW HVDC offshore platform and a 525 kV bipolar cable system [62].

1a-9 Major Equipment Categories

1a-9.1 Introduction

HVDC schemes include the following four main groups of equipment [26]:

- Converters: The design of converters has evolved over time. Converters provide the connection between ac and dc-sides of the HVDC scheme, and a HVDC system requires at least one converter (ac-to-dc converter, rectifier) at the sending end and one converter (dc-to-ac converter, inverter) at the receiving end.
- Transformers: As noted earlier, transformers made it possible to convert between different voltage levels, and hence use of different ac voltage levels for generation, transmission, distribution, and various end-use applications. In HVDC schemes transformers are used to align ac system voltages with the converter design.
- Conductors: Bipolar HVDC schemes require two lines between the converter stations, while high voltage alternating current transmission requires three lines. Since HVDC allows for efficient long-distance transmission, these lines can be very long. Each line can consist of multiple conductors per phase and the lines can be constructed as overhead lines and/or cables (underground or undersea).
- Protection and Control: The power flow through an HVDC link can be controlled independently of the phase angle between source and load. HVDC schemes require communication between the terminals and can improve stability of interconnected networks. Protection and control systems are often integrated into computers at HVDC installations, and they provide essential services to ensure safe, reliable, and efficient operation of the HVDC systems.

The converter and associated components can be considered the most vital element in a HVDC facility. Some other main physical equipment types are introduced below. As noted earlier, since most HVDC installations in North America are based on line commutated converter technology and many components are similar, the below section on LCC HVDC equipment will go more in depth than the following section on VSC HVDC equipment. In case of a bipolar configuration, each of the poles have their own group of each of the above major equipment groups, i.e., each (or at least most) major equipment group is duplicated for each pole.

Additional information about some equipment categories and Technology Readiness Levels (TRLs), including e, g., HVDC circuit breakers, dynamic line ratings (DLRs), hybrid ac/dc overhead lines, line commutated converters (LCCs), and voltage source converters (VSCs), are available on European Network of Transmission System Operators for Electricity’s (ENTSO-E) Technopedia website [54].

1a-9.2 Line Commutated Converters

LCC HVDC stations include valve hall and converter transformers as well as ac and dc switchyards. Equipment can, e.g., be categorized into the following main categories:

- Valve hall
  - Converters (one if monopolar and two are bipolar)
  - Valve Control Equipment
  - Pole Control Equipment
  - Valve Cooling Equipment
  - Valve Cooling Control Equipment
  - DC Bus Equipment
- Converter Transformers
  - Load Tap Changers
- AC Switchyards
  - AC Filter Banks
  - AC Shunt Capacitor Banks
  - AC Bus Equipment
  - AC Circuit Breakers
  - AC Switchgear
  - Shunt Reactors (optional)
  - Electrode Line Equipment (if applicable)
  - Control and Protection Systems
  - Power Line Carrier (PLC) Filters (if applicable)
- DC Switchyards
  - DC Smoothing Reactors
  - DC Filter Banks
  - DC Switchgear
- DC Lines
  - Overhead Line, or
  - Cables (underground or undersea)
  - Neutral Conductor (if applicable)

1a-9.2.1 LCC HVDC Converters

Use of semiconductor technology for direct current applications allowed for development of reliable converter valves with series-connected devices. The large number of series-connected semiconductors allowed for use in high voltage direct current applications. Series connection of multiple individual semiconductors required additional components to be added to each valve to achieve a uniform voltage distribution between the individual semiconductor units. The additional passive components also function as protection for thyristors from overvoltages, excessive rate of rise of voltages (dv/dt), and rate of rise of inrush currents (di/dt) [55].

LCC converters are conventionally designed as a 12-pulse converter, where each incoming phase of each pole is referred to as a quadruple valve, which consists of combination of two six-pulse valve groups connected into series. One of the six-pulse valves are connected to a Y/Y transformer winding and the other to a Y/Δ transformer winding and thereby eliminating 5^{th} and 7^{th} harmonics. This 12-pulse converter configuration hence requires less harmonic filtering equipment. A bipolar configuration thus includes one 12-pulse converter per pole, each with three quadruple valves which each consists of two six-pulse valves fed from a Y/Y transformer winding and the other to a Y/Δ transformer winding, respectively.

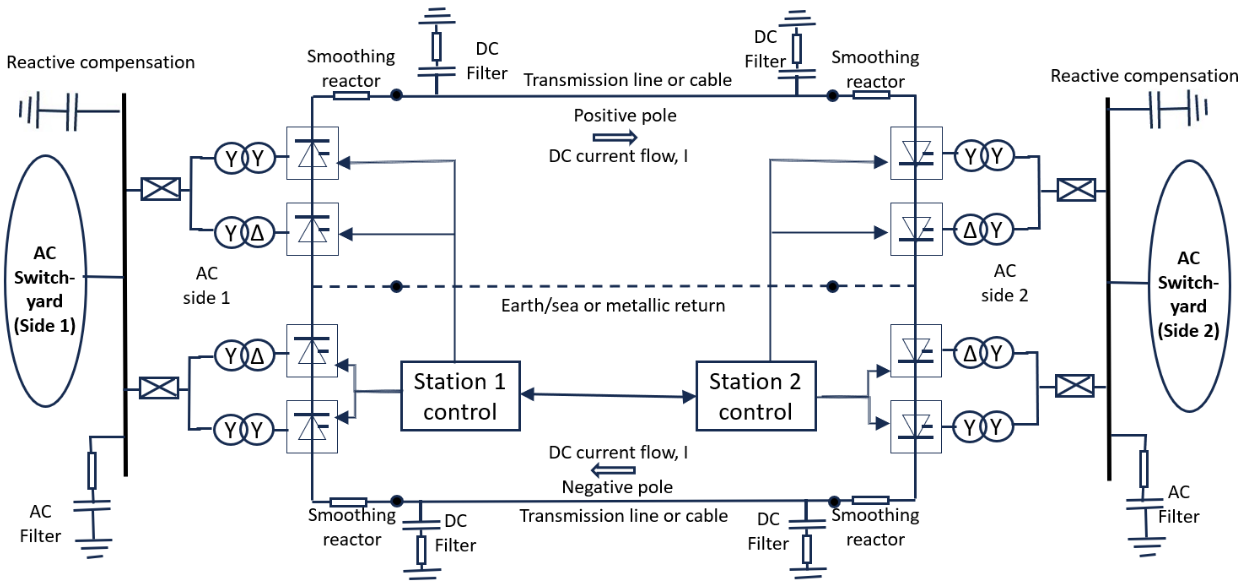

Figure 1a – 23: HVDC LCC Scheme [49]

When designing converter valves, both current through and voltage across the thyristors should be optimized for the specific power rating of the HVDC scheme. The thyristors must also be operated below their maximum temperature capability since higher temperatures reduce their capabilities of sustaining voltages in forward and reverse blocking directions. Another important design consideration is that the valves should be able to withstand a short-circuit, e.g., between the positive and negative sides on the dc-sides of the valve [63]. To have a consistent design that meets seismic requirements when required, most 12-pulse quadruple valves are hung from the ceiling of the valve hall building.

Line Commutated Converters 'consume' relatively high levels of reactive power, up to 50% to 60% of the level of active power transferred during operation. This reactive power is compensated by installed ac shunt capacitors and ac filter banks. Since converter operation also results in harmonics on the ac-side, a large part of the ac switchyard is taken up by ac filter and shunt capacitor banks. It is important to reduce the level of harmonics imposed on the ac system, since ac harmonic flows e.g., can cause interference with (non-fiber) telecommunication systems.

1a-9.2.2 Thyristor Firing System

To avoid unnecessary overvoltages on the thyristors, all applicable thyristors must be fired simultaneously. Earlier LCC HVDC schemes used a small positive voltage pulse to the gate to trigger the thyristor into its on (conducting) state, while modern use a light pulse. Fiber optics are used as light guides to carry the firing pulse to each thyristor. Information related to the status and condition of the thyristor is also communicated via a fiber optic system providing information used by the control and protection system from the thyristor to the control unit. Supervision of each individual thyristor facilitates valve maintenance [63].

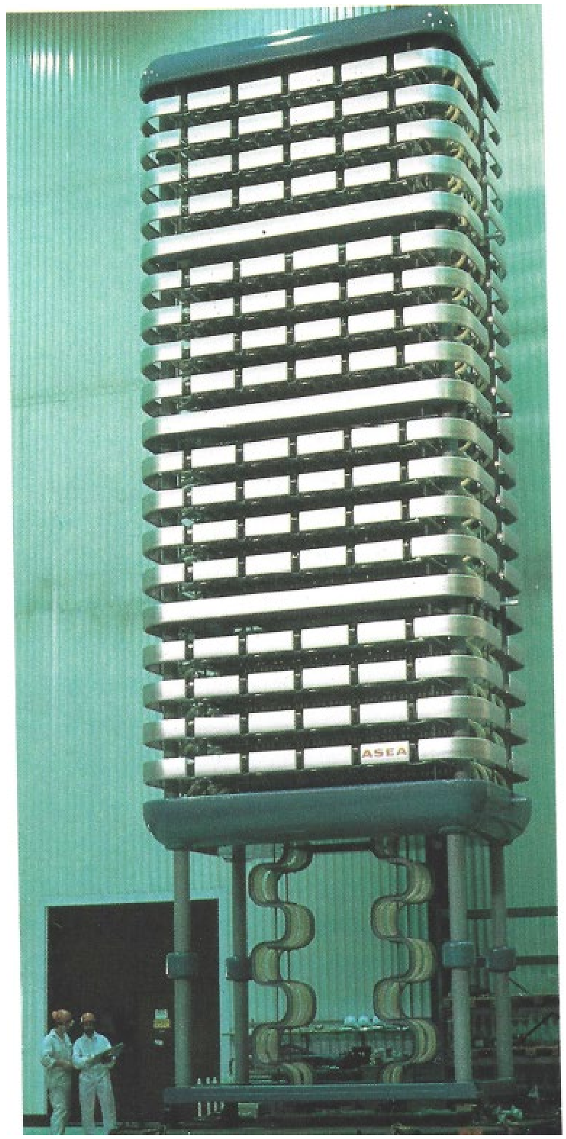

Figure 1a – 24: LCC HVDC Quadruple Valve [31]

Since thyristors in practical applications are not pure ideal switches, and technical difficulties arise from having many thyristors connected in series, each thyristor valve contains a firing system with overvoltage protection and thyristor monitoring system. The electric circuit of a thyristor also includes a saturating reactor providing a large inductance to protecting thyristors from high inrush currents immediately after the valve has been receiving a firing pulse. Overvoltage protection of thyristor valves can be accomplished by connecting a metal oxide surge arrester between the terminals of the valve [55].

1a-9.2.3 Converter Transformers

Larger converter transformers can be constructed as single-phase three-winding units, i.e., one primary winding towards the external ac system, and for a 12-pulse converter with two secondary windings, where one secondary winding is connected in Y/Y configuration and the other secondary winding is connected in Y/Δ configuration. Converter transformers, for a 12-pulse converter, can be constructed as three-phase two-winding units, where one unit is connected in Y/Y configuration and one unit is connected in Y/Δ configuration. Converter transformers can also be constructed as single-phase two-winding units.

Each pole of a 12-pulse line commutated converter can be connected to an external three-phase ac transmission system via three single-phase three-winding units, six single-phase two-winding units, or two three-phase two-winding units. The secondary windings are connected to a quadruple valve inside the valve hall via bushings, i.e., in 12-pulse converter configurations each of the three phases of the ac system is available and connected to the quadruple valves via both Y/Y and Y/Δ transformer windings.

A difference between HVDC converter transformers and 'conventional' ac system transformers is that converter transformers are subject to dc voltage insulation stress in addition to normal ac voltage stress. The additional stress occurs on the valve windings, i.e., the secondary windings connecting to the quadruple thyristor valves, and particularly at the end of the windings and at the connection to the bushings. While direct voltage distribution in the converter transformer is determined by the resistance, the ac voltage distribution is determined by the capacitance [64].

These converter transformers, sometimes referred to as 'HVDC transformers,' are almost always equipped with tap changers. The tap changers are used to optimize the dc voltage level to keep the delay angle and the extinction angle close to their target values, which is important with respect to the magnitude of reactive power consumption in the converter. The transformer tap changers can also compensate for deviations of the ac bus voltage.

If lowering the dc voltage while operating at normal power transfer levels, it is possible that the range of the converter transformer tap changer is not sufficient to maintain normal firing and extinction angles. Since the harmonics are mainly driven from the firing/extinction angles and dc current levels, such an operation would result in increased harmonic levels [65].

The transformer leakage inductance determines the thyristors short-circuit level and is also part of the dc-side inductance. The leakage impedance of converter transformers limits the short-circuit currents through the thyristor valves, where leakage impedances below approximately 12% or above approximately 22% are associated with increased manufacturing costs.

1a-9.2.4 AC Filters and Shunt Capacitor Banks

Line commutated converters 'absorb/supply' relatively large amounts of reactive power, i.e., up to 50% to 60% of the active power transfer level. Harmonic filters are installed on the ac-side for filtering the current, which as described above includes harmonics due to converter operation. Both harmonic filters and shunt capacitor banks are used to compensate for the reactive power absorption of converters, i.e., for maintaining the reactive power balance, by automatically switching in and out to meet both harmonic and reactive power performance limits.

Since the reactive power consumed by the converter valves varies with the transmitted power during operation, the reactive power balance is maintained by switching in and out of filter and shunt capacitors banks. The ac filter banks are together with the shunt capacitor banks are automatically switched in or out depending on operating conditions as determined by the HVDC scheme's reactive power and voltage control systems.

Filter banks consist of capacitors, reactors, and resistors, either as tunes or bandpass filters, to reduce the flow of harmonic current into associated ac system. During light load conditions, when line commutated converters 'consume' relatively small amounts of reactive power there may be a need to provide additional inductive reactive power compensation to avoid high voltage situations. This situation can be accentuated by the requirements of having a certain minimum amount of harmonic filter capacity always connected to satisfy harmonic performance requirements.

Filter banks are used to mitigate and reduce harmonics to be within acceptable ranges and thereby prevent damage to equipment in the ac system. IEEE Standard 1531-2020 'IEEE Guide for the Application and Specification of Harmonic Filters' [66] provides guidelines for specification of components, protection, and control of harmonic filters. This IEEE standard provides guidelines for application of passive shunt harmonic filters to reduce the harmonic distortion on the ac system.

The IEEE Standard 519-2014 'IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems' [67] establishes criteria for voltage and current harmonics distortion in electrical system design. Since static power converters are large nonlinear loads, which change the sinusoidal nature of the ac power current, thereby resulting in the flow of harmonic currents in the ac power system that can cause interference with communication circuits and other types of equipment. These harmonic currents also lead to increased losses and heating in electromagnetic devices such as motors and transformers.

The ac filter banks provide harmonic mitigation by selectively reducing or eliminating unwanted higher frequency components. These filters are shunt connected, which provides a path to ground for the selected harmonics. Harmonic filters for LCC HVDC applications are often designed as tuned filters for each harmonic, which in case of a 12-pulse converter primarily would be 11^{th} and 13^{th} harmonics, combined with high-pass filters for higher harmonics. These tuned or high pass ac harmonic filters are typically constructed with a capacitor bank connected to the high voltage ac bus in series with an appropriately tuned circuits consisting of reactors, resistors, and capacitors, i.e., RLC circuits. Another option is to connect STATCOM(s) to the high voltage ac bus, which could reduce the required amount of ac filter and shunt capacitor banks as well as the number of switching operations on these banks but likely comes at a higher cost.

1a-9.2.5 AC Shunt Reactors

The ac switchyard could also have shunt reactors installed on the ac-side to provide reactive power compensation under high voltage conditions. As the reactive power consumption increases when ramping up the power transfer on a LCC link, the ac voltage accordingly decreases, and any installed shunt reactors might be disconnected if there is enough margin not to exceed high voltage limits after the shunt reactor is disconnected. Shunt reactors combined with harmonic filters and shunt capacitor banks allow for reactive power and voltage control during varying operating conditions. A reactive power/voltage control system can be programmed to not to have more shunt reactors connected than allowed for by the upper voltage limit.

1a-9.2.6 DC Filters

Ratings and specifications for both ac and dc filter banks should be selected to satisfy e.g., overvoltages and transient ratings, protection requirements, reliability considerations, audible noise limits. The converter transformers, commonly located outdoors, can generate significant levels of audible noise. As noted in the section on DC Harmonics, a line commutated converter acts as a source of 12th, 24th, 36th, etc. voltage harmonics on the dc-side. Design of dc filters for potential mitigation of telephone interference is based on the theory of inductive coupling.

DC filters consist of capacitors and reactors to reduce current or voltage ripple on dc line. An important concern with dc-side harmonics, apart from the risk of inductive coupling with communication systems, is the issue of dc circuit resonance. The risk of dc circuit resonance issues at a critical frequency should be considered. This type of resonance issues may lead to extreme levels of harmonic currents and voltages. If this type of dc resonance occurs, it can affect component rating and the viability of stable control [56].

1a-9.2.7 DC Smoothing Reactors

A large series reactor on the dc-side smoothens the dc-side voltage waveform and produces a constant dc voltage. DC smoothing reactors are often connected on the dc line-side in series with the converter to reduce the current harmonic in the direct current and reduce the stress on the thyristor valves due to transients. Transients resulting in high rate of rise for the dc current can be caused by dc line faults, e.g., from lighting strikes, and commutation failures, where the dc smoothing reactors help reducing this stress by limiting the fault current and rate of rise current, so called fast front transients [63].

Reducing the rate of rise of dc currents during faults is important for recovering the HVDC system following a fault. Reducing the rise of the dc current after a fault improved chances of next commutation, i.e., 30° later, being successful. By smoothing the direct current, the dc smoothing reactors also play a part as a series filter [55]. These dc smoothing reactors can be constructed as dry type air-insulated air core reactors or oil insulated reactors. Since direct current applications have a tendency to attract pollution in form of small particles, smoothing reactors can be installed in large climate-controlled buildings [47] or outside on the dc-side of the valve hall building.

1a-9.2.8 Switchgear

The ac and dc switchyards include high voltage switchgear which are used to connect or disconnect equipment or lines for operational or protection purposes. Both the ac and dc yards include disconnects and earth switches used for switching in and out of equipment and reconfiguration and safe maintenance operation purposes. Circuit breakers can be used in the ac switchyard to switch filter and shunt capacitor banks on the ac-side as required to reduce harmonics and provide the appropriate level of reactive power compensation.

1a-9.2.9 Cooling System

The first generation of thyristor valves were air cooled via heat exchangers. Special protections such as filtering the air to avoid insulation problems due to pollution in the valve hall. Larger thyristors with higher currents required even more efficient cooling systems. Development of modern cooling system started in the 1970s, where the two main alternatives were a water-cooled system, and a cooling system based on freon. Advantages of using water included that it has a higher heat capacity, would not require special permits, and there were very good experiences from water cooling with de-ionized water from mercury-arc valves [68].

Since the power handling capability of the thyristors is dependent on the temperature of the semiconductor wafer, the cooling system is very important for adequate operation. The immediate temperature rise of the semiconductor wafer during short duration overcurrents are mostly dependent on the heat capacity and thermal conductivity of the cooler, and not on the external cooling medium. A more efficient cooling system will by reducing the pre-event temperature allow for a higher temperature rise during the transient [63].

Water used to cool a thyristor valve must, due to the high potential difference, be de-ionized to obtain a sufficiently high electric resistance. In order to de-ionize the water and limit the amount of oxygen a special water processing unit is used in the fine water system. Using large thyristors together with efficient water-cooling systems allow for achieving a considerable overload capability at a relatively moderate cost increase. In order to provide equal cooling for all thyristors in a quadruple valve, the modules are often cooled with two parallel cooling circuits [68].

1a-9.2.10 Control and Protection Systems

HVDC converter stations are equipped with advanced computerized systems for control and protection (C&P) as well as monitoring. The major parts of the control and protection system is located in a control room, which has restricted access. The operators may be located in a separate control room, for e.g., fire safety reasons, which can be located apart from the valve hall. The monitoring system includes supervisory control and data acquisition (SCADA) functions for efficient communication and control of the HVDC scheme and its equipment.

Control systems are often divided into local and master level controllers, where the master controller provides controls related to operation of the full HVDC scheme. While the master control system can allow for remote operation from one terminal at another terminal, although this is allowed it may not be ‘normal’ operation practice and could be ‘blocked’ by settings of the master control mode at each station. The Quebec - New England Phase II HVDC Transmission System was the world’s first multi-terminal bipolar HVDC system where three stations were interconnected and operated under a common master control system.

An important unit of the control system is the firing control system which generated firing pulses to the thyristor valves. Protection systems, often included as part of the overall control and protection system for the HVDC terminal, are of vital importance in order to protect valves and other equipment against excessive stress. High overvoltages can usually be avoided by fast action of the protection system. The man-machine interface used by the operators and engineers at a HVDC facility constitute an important tool for safe and reliable operation [68].

Control and protection systems are designed with full redundancy to allow for satisfactory operation during both normal and abnormal (contingency) situations. While control and protection systems for LCC systems are well established and based on fairly consistent and standardized design principles, control and protection systems for hybrid LCC-VSC schemes, and in particular for multi-terminal networks, is an active area of research.

If HVDC schemes are to be used for damping of electromechanical oscillations in ac systems and the power required for the modulation, rectifier and inverter controls must be coordinated. The required modulation rate determines the required transmission rate of the telecommunication system [55]. Several HVDC installations world-wide, e.g., Pacific Intertie in the U.S, Itaipu in South America, and Fenno-Skan between Sweden and Finland, are used to provide damping of power system oscillations when required. A theoretical analysis of use of active and reactive power modulation of HVDC transmission links to damp slow oscillations in power systems is e.g., provided in a paper by Dr. Thomas Smed and Prof. Göran Andersson [69].

1a-9.2.11 Earth Electrodes

For HVDC schemes allowed to operate in monopolar mode, ground (a.k.a. earth) electrodes establish the required connection to earth at locations some distance away from the converter stations, thereby providing an earth return circuit. Due to potential long-term use of earth as the return circuit for the dc current, design of earth electrodes for HVDC schemes involve several aspects including multiple electrical and thermal aspects, including personal and animal safety, soil characteristics, and possible corrosion.

Since the resistivity of the upper layer often is high, typically in the order of 4,000 Ωm, earth electrodes cannot be places directly in contact with such high resistance [55]. Consequently, earth electrodes should be located in areas with low resistivity earth layers or use sea water as conductive medium to form the required dc current return path. An electrode line is used to connect the converter station with the earth electrode location.

Locating earth electrodes away from the converter station, avoids the risks of interference or corrosion in the converter station grounding system and prevents direct currents in the earth return circuit entering converter transformers via the primary neutral causing dc saturation. Locating low resistance earth electrodes in low resistivity earth layers or use of sea water results in low dc electric potentials and potential gradients at the surface of earth [55]. This results in improved safety by reducing risks of step and touch potentials. Some additional considerations for earth electrodes were provided in the section on HVDC Topologies.

1a-9.2.12 DC Lines

HVDC schemes can be classified in accordance with their number of lines (overhead and/or cable) and configuration on the dc-side, e.g., monopolar with a single line, bipolar with two lines, and back-to-back system with both converters very close to each other, often inside the same building, connected via a very short dc conductor. Large HVDC schemes are often constructed as bipolar systems with two separate poles, connected via overhead conductors, underground/undersea cables, or combinations thereof.

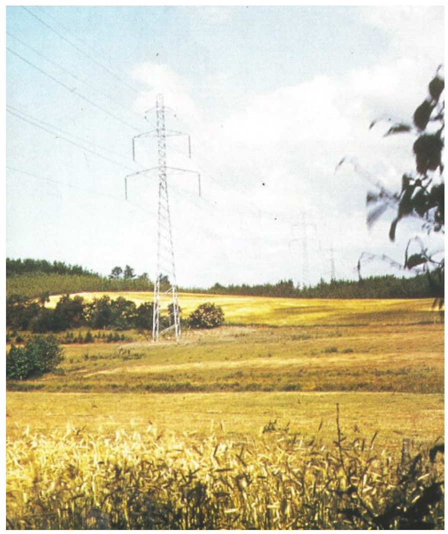

Figure 1a – 25: Bipolar HVDC Overhead Transmission Line [37]

An important design factor, affecting e.g., tower designs, for a bipolar HVDC transmission line is the required minimum clearing distance. HVDC lines are most often protected against direct lightning strikes by the installation of an overhead ground wire. Close to the location of HVDC terminals, there are sometimes two overhead ground wires to increase the reliability of not having a direct lightning strike in these sections [55].

If use of earth electrodes is not allowed, even for short periods of time, availability of the HVDC scheme can be achieved by connecting the neutral bus at each terminal with a third conductor. This conductor is referred to as a neutral bus conductor, which in the event of an outage of one pole allows for approximately 50% of the nominal power to continue to be transported for an unlimited period of time. The neutral bus conductor can be designed with a cross section corresponding to the thermal current limit since transmission losses play a less important role during single pole operation, i.e., emergency operations [55].

While design of HVDC schemes with overhead transmission lines do not differ so much from design with underground or undersea transmission cables, there are some important phenomena to keep an eye on. The capacitance of ac cables is much higher than for overhead lines, resulting in current in HVAC reaching their nominal values already at relatively short distances. The 'break-even distance' justifying consideration of the HVDC option is hence much shorter for cables than overhead lines.

Figure 1a – 26: An Older Cable Ship ('Skagerrak') [37]

Figure 1a – 27: Cross-Section of a 250 kV DC Cable [37]

1a-9.3 Voltage Source Converters

1a-9.3.1 Hybrid HVDC Scheme

The Skagerrak HVDC schemes providing an asynchronous interconnection between Norway and Denmark was originally (Skagerrak 1 & 2) commissioned in 1977 as a 500 MW ±250 kV HVDC scheme. The scheme has been expanded over the years and continues to evolve. Skagerrak 1, 2, and 3 were built with line commutated converters, while voltage source converter technology was selected for the most recent expansion (Skagerrak 4) rated at 700 MW ±500 kV. Skagerrak thus constitutes a HVDC schemes Combining LCC and VSC in a hybrid bipolar arrangement [70].

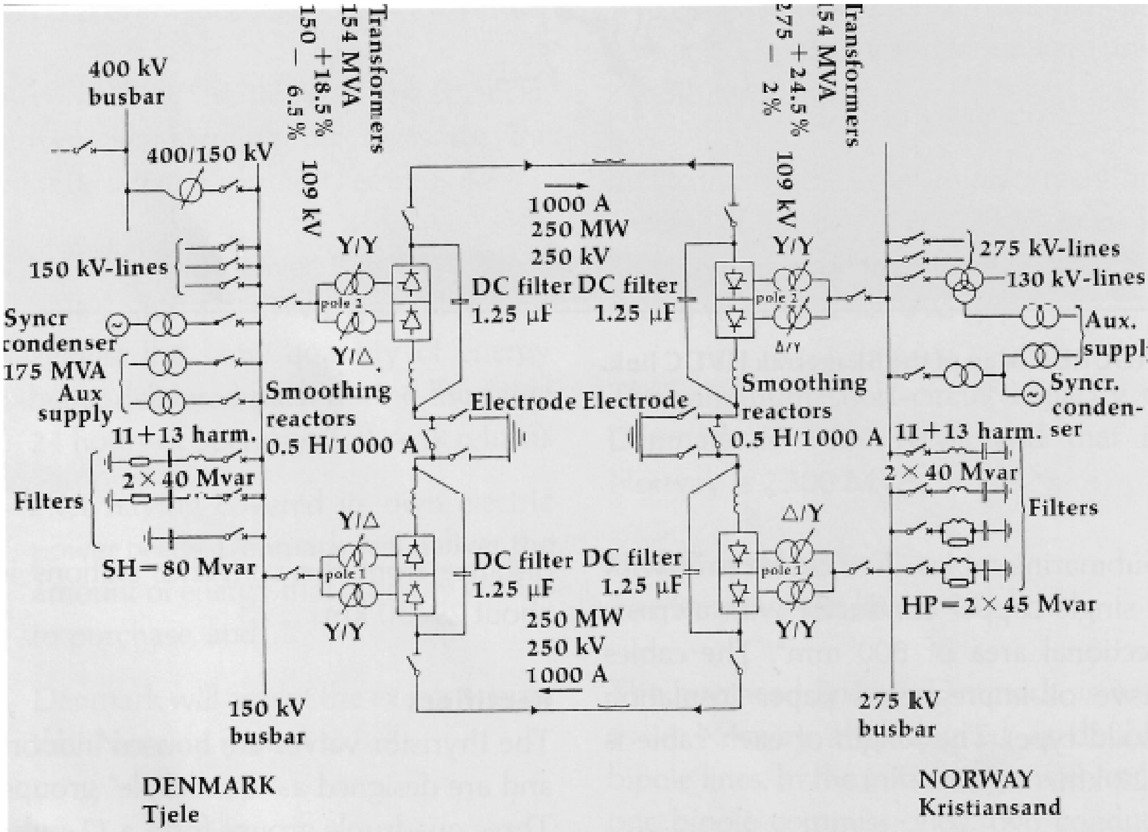

Figure 1a – 28: The Skagerrak 1 & 2 (original) HVDC LCC scheme [37]

1a-9.3.2 Equipment Categories

VSC HVDC stations also include valve hall as well as ac and dc switchyards, and most installations include converter transformers. Equipment can, e.g., be categorized into the following main categories:

- Valve hall
  - Converters
  - Converter Control Equipment
  - Valve Cooling Equipment
  - Valve Cooling Control Equipment
  - DC Bus Equipment
- Converter Transformers (most installations)
  - Load Tap Changers (optional)
- AC Switchyards
  - AC Filter Banks (optional)
  - AC Bus Equipment
  - AC Circuit Breakers
  - AC Switchgear
  - Control and Protection Systems

- DC Switchyards
    - DC Link Capacitors
    - DC Switchgear
    - DC Circuit Breakers (optional; future)
- DC Lines
    - Cables (underground or undersea; common)
    - Overhead Line

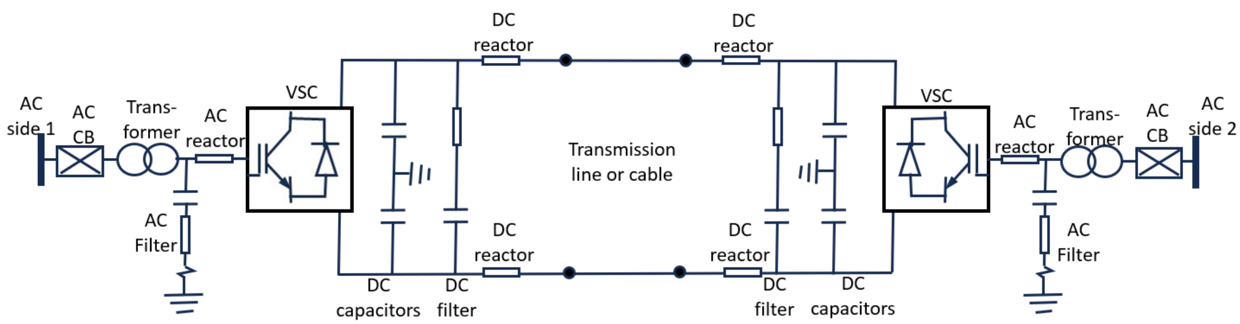

Figure 1a – 29: HVDC VSC Scheme [49]

1a-9.3.3 VSC Characteristics

As the name indicates, use of a voltage source converter (VSC) for power conversion implies the presence of a voltage source on the dc-side. In a VSC HVDC scheme, there is a capacitor connected in parallel across each voltage source converter, serving like a 'voltage port,' on the dc-side of the converter. The so constructed voltage source maintains the prescribed voltage across its terminals (almost) irrespective of the magnitude of current flowing through the source [55].

Voltage source equipment has been designed to allow for transmission of power, underground and underwater, over long distances. In a VSC, the dc-side is as described above strongly capacitive, i.e., voltage stiff. The dc-side capacitors help stabilize the dc voltage. In contrast to the thyristors in a LCC HVDC scheme, the IGBTs in a VSC HVDC scheme have to be designed to withstand high voltage for a substantial period of its operating time.

A typical IGBT building block consists of a single switching (semiconductor) device, snubber components, and a gate drive, including overvoltage, undervoltage, and overcurrent protection. Fiber optics is used for communication of trigger pulses and for diagnostic purposes [55]. Voltage source converters can be constructed as either half-bridge or full-bridge modules.

Since a VSC acts like a voltage harmonic source, some of these harmonics will appear at the point of interconnection to the ac network. The system impedance at may appear capacitive at certain frequencies, which may create series resonance. Thus, comprehensive harmonic studies must be performed to determine the frequency variation of the ac system impedance under varying operating conditions [55].

1a-10 Summary of main learning points

Like the development of alternating current in the beginning of the 20th century, which so much has influenced the development of today's electric power industry and our society as a whole, the development of high voltage direct current technology is presently seeing a renaissance based on the on-going electrification and associated need to build out electric energy generation capacity. The rapid development of HVDC technology is a testament to the growing need for large-scale efficient and reliable electric power transmission systems [71].

Main learning objectives for this introductory module on high voltage direct current technology were to present a historic expose of the development of HVDC, introduce objectives and components used in HVDC systems, characterize principal types of HVDC configurations, and introduce basic control modes for HVDC systems.

After a historic expose, including HVDC and semiconductor developments, this module discussed considerations to consider when deciding between HVDC and HVAC and introduced different types of monopolar and bipolar HVDC configurations. Basic operation and characteristics for both line commutated converters and voltage source converters, including an introduction to principles for ac to dc conversion based on six-pulse and 12-pulse converters, types of dc-side topologies, and basics of voltage and reactive power control were provided. This was followed by sections on major equipment categories for LCC and VSC schemes, before this module was concluded by this summary of introduced concepts.

Additional information providing more in-depth understanding of various HVDC applications and configurations, including control modes, is provided in other modules of this HVDC Learn material. Enjoy your continued educational journey.

The following two pages provide some questions and problems for the user to review and reinforce main learning points from this module, Module 1a 'Introduction to HVDC Technology.'

Problems

Problem 1: What was the Pearl Street station and who was the inventor behind it?
Solution: The Pearl Street station was the first permanent commercial power plant, with an underground distribution network. On 4 September 1882, Thomas Edison's Pearl Street station began supplying electricity to a Manhattan block, a one-quarter square mile (0.65 square km) area.

Problem 2: Which technical invention enabled longer distance transmission of electric power using by use of alternating current (ac)?
Solution: Longer distance transmission of electric power using alternating current became feasible first with the development of transformers for stepping-up or stepping-down voltages.

Problem 3: Who developed the first practical transformer?
Solution: The American inventor and engineer William Stanley developed the first practical transformer in 1886. Stanley, supported by George Westinghouse Jr., installed the first practical single-phase ac transmission system with transformers at Great Barrington, Massachusetts.

Problem 4: Which inventor pioneered polyphase ac power systems and played an essential role in the war of currents during the late 1880s and early 1890s? Mention some of his inventions.
Solution: The Serbian American engineer and inventor Nikola Tesla, who in November of 1887, Tesla filed a series of seven US patents in the field of polyphase ac motors, power transmission, generators, transformers, and lighting, which were approved without challenge.

Problem 5: Who has been referred to as the 'Father of High Voltage Direct Current' power transmission, and why?
Solution: Uno Lamm who won several professional awards has often been referred to as the 'Father of High Voltage Direct Current' power transmission. Some information about Uno Lamm and his work developing HVDC technology is provided in (and around) Section 1a-3.2.

Problem 6: When did the world's first commercial HVDC transmission project start commercial operation and where was it located?
Solution: The world's first commercial HVDC transmission HVDC link was commissioned and initiated commercial operation in 1954. It was built between the Swedish mainland the island of Gotland (in the Baltic).

Problem 7: Which three types of converter valves have been used in commercial HVDC schemes?
Solution: Mercury-arc valves, thyristors, and insulated-gate bipolar transistors (IGBTs).

Problem 8: Describe some characteristics of the two types of semiconductor-based converter valves used today in commercially operated HVDC schemes?
Solution: Basic characteristics of thyristors and insulated-gate bipolar transistors (IGBTs) are described in Sections 1a-4.3 and 1a-4.4, respectively.

Problem 9: Describe some economic and technical considerations to have in mind when selecting between HVAC and HVDC solutions. Briefly explain break-even distance for investment costs.
Solution: Some technical consideration on selection between HVAC and HVDC solutions are provided in Section 1a-5.3, and Figure 1a – 15 illustrates investment cost as function of distance for HVAC and HVDC links.

Problem 10: Discuss differences between power electronics-based line commutated converters (LCCs) and voltage source converters (VSCs) technology.
Solution: Some differences between line commutated converters and voltage source converters are presented in Section 1a-6.3.

Problem 11: Provide some characteristics for major equipment categories for:

a. Line commutated converters (LCC)
b. Voltage source converters (VSC)

Solution: Major equipment categories of HVDC schemes are discussed in Section 1a-9.2 for LCC and Section 1a-9.3 for VSC.

Problem 12: Derive the formula for average voltage on the dc-side of a six-pulse line commutated rectifier with a delay angle α.
Solution: $V_{d\alpha} = V_{d0} - \Delta V_{\alpha} = \frac{3\sqrt{2}}{\pi}\left(\int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \cos\omega t\, d(\omega t) - \int_0^{\alpha} \sin\omega t\, d(\omega t)\right) = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha$
See Section 1a-7.1 for additional information.

Problem 13: Calculate the relationship between average voltage on the dc-side and line-to-line voltage, for a line commutated converter with a delay angle α.
Solution: $3\sqrt{2}/\pi$; see formula for $V_{d\alpha}$ in Section 1a-7.1.

Problem 14: Compare six-pulse and 12-pulse line commutated converters by describing:

a. Differences, including advantages of 12-pulse converters
b. Converter transformer winding configurations

Solution: Waveforms and basic characteristics of six-pulse and 12-pulse LCCs are described in Sections 1a-7.1 and 1a-7.2 for Problem a, and in Sections 1a-9.2.1and 1a-9.2.3 for Problem b.

Problem 15: Calculate average dc-side voltage and plot voltage waveforms for a three-phase full-bridge thyristor (six pulse) line commutated converter, assuming it supplies 10 kW of power with ac line side reactance Ls = 0 and ac three-phase (line-to-line voltage V_{LL} = 480 V (rms) at 60 Hz.

a. The delay angle α = 0°
b. The delay angle α = 30°
c. The delay angle α = 150°

Solution: Use formula for $V_{d\alpha}$ in Section 1a-7.1 to calculate average dc-side voltage. Voltage (and current) waveforms can be found in many textbooks on HVDC, e.g., Chapter 3 in Kimbark [72].

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