HVDC Transmission: Technology Review, Market Trends and Future Outlook

Abdulrahman Alassi[a,*], Santiago Bañales[a], Omar Ellabban[a], Grain Adam[b], Callum MacIver[b]

[a] *Iberdrola Innovation Middle East, Doha, Qatar*

[b] *Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom*

* *aalassi@iberdrola.com*

Abstract:

HVDC systems are playing an increasingly significant role in energy transmission due to their technical and economic superiority over HVAC systems for long distance transmission. HVDC is preferable beyond 300-800 km for overhead point-to-point transmission projects and for the cable based interconnection or the grid integration of remote offshore wind farms beyond 50-100 km. Several HVDC review papers exist in literature but often focus on specific geographic locations or system components. In contrast, this paper presents a detailed, up-to-date, analysis and assessment of HVDC transmission systems on a global scale, targeting expert and general audience alike. The paper covers the following aspects: technical and economic comparison of HVAC and HVDC systems; investigation of international HVDC market size, conditions, geographic sparsity of the technology adoption, as well as the main suppliers landscape; and high-level comparisons and analysis of HVDC system components such as Voltage Source Converters (VSCs) and Line Commutated Converters (LCCs), etc. The presented analysis are supported by practical case studies from existing projects in an effort to reveal the complex technical and economic considerations, factors and rationale involved in the evaluation and selection of transmission system technology for a given project. The contemporary operational challenges such as the ownership of Multi-Terminal DC (MTDC) networks are also discussed. Subsequently, the required development factors, both technically and regulatory, for proper MTDC networks operation are highlighted, including a future outlook of different HVDC system components. Collectively, the role of HVDC transmission in achieving national renewable energy targets in light of the Paris agreement commitments is highlighted with relevant examples of potential HVDC corridors.

Key Words: *HVDC Transmission, HVDC Challenges, LCC-HVDC, VSC-HVDC, DC Cables, DC Circuit Breakers, HVDC Outlook, Multi-Terminal DC Grids, Renewable Energy*

Word Count: ~~13,092~~ (v1), ~~15,804~~ (v2), 16,600 (v3) (*including the abstract & abbreviations list*)

List of Acronyms:

ACCB	AC Circuit Breaker	**MVDC**	Medium Voltage Direct Current
AGC	Automatic Generation Control	**MMC**	Modular Multilevel Converter
B2B	Back-to-Back	**MTDC**	Multi-Terminal DC Network

CCC	Capacitor Commutated Converters	**OLTC**	On-Load-Tap-Changer
CAGR	Combined Annual Growth Rate	**OH**	Overhead Transmission Line
CSP	Concentrated Solar Power	**PLL**	Phase-Locked-Loop
C2L	Conventional 2-Level VSC Converter	**PWM**	Pulse-Width-Modulation
XLPE	Cross-linked Polyethylene Cable	**RES**	Renewable Energy Source
CSC	Current Source Converters	**RCB**	Residual Circuit Breaker
DCCB	DC Circuit Breaker	**ROW**	Right-of-Way
DER	Distributed Energy Resource	**SC**	Short Circuit
GEI	Global Energy Interconnection Vision	**SCL**	Short-Circuit Level
HB	Half-Bridge MMC Submodule	**SCR**	Short-Circuit Ratio
HVAC	High Voltage Alternating Current	**PV**	Solar Photovoltaic
HVDC	High Voltage Direct Current	**STATCOM**	Static Synchronous Compensator
IGBT	Insulated-Gate Bipolar Transistor	**SVC**	Static VAR Compensator
IGCT	Integrated Gate-Commutated Thyristor	**SFCL**	Superconducting Fault Current Limiter
LCC	Line Commutated Converter	**TCSC**	Thyristor-Controlled-Series-Capacitor
LCS	Line Commutation Switch	**UHVDC**	Ultra High Voltage Direct Current
MCB	Main Circuit Breaker Branch	**UG**	Underground Transmission
MI	Mass-Impregnated Cable	**VSC**	Voltage Source Converter

1. Introduction:

To meet the growing energy demand, the global annual electricity generation is anticipated to surpass 38,000 TWh by 2040 compared to 24,000 TWh in 2016. The contribution of renewable energy sources is expected to approach 51% of the total generation mix by 2040 compared to 22% today [1]. This requires continuous network infrastructure development with large investments to maintain efficient energy generation, transmission and distribution. That is, many large-scale renewable energy power plants are located far from main demand centres, thus requiring efficient bulk energy transmission for very long distances [2, 3]. Similar efficient and cost-effective transmission criteria is required for offshore wind farms that have increased their market share recently, especially in Northern/Western Europe [4-6].

In contrast, the interconnection of regional and national electricity markets is evolving globally for energy trading and increasing the security of supply level. For example, the EU has recently set a target for each country to achieve a level of interconnected capacity with neighbouring markets that is equivalent to 15% of its installed capacity by 2030 [7].

1.1. HVDC Transmission Background

Bulk energy transmission/interconnection is feasible using both HVAC and HVDC links. Historically, HVAC has been the main transmission technology benefiting from the early development of AC transformers that allowed for high voltage AC transmission for longer distances and lower losses, thus settling the Edison and Tesla "War of Currents" in Tesla's favour. However, the consequent development of mercury arc valves and their widespread adoption by 1930s gradually paved the way for DC to re-enter the transmission market as they also allowed for energy to be transmitted at higher DC voltages.

The first commercial HVDC link was built by ABB in Sweden by 1954 after years of experimentation. The Gotland 1 link spanned 98 km, carrying 20 MW at 100 kV [8-10]. The use of HVDC transmission evolved further with the development of thyristor valves in the 1960s, overcoming several drawbacks of their predecessors. The main advantages were reduced weight and space requirements for thyristors, with increased efficiency, power density and control flexibility. As a result, thyristor based links quickly dominated the HVDC landscape. Reference [8] presents an interesting review of the early HVDC market transition from mercury-arc to thyristor switching valves.

Further innovation led to the development of Insulated-Gate Bipolar Transistor (IGBT) valves in 1980s [11, 12], which were introduced to the HVDC market by the late 1990s [13]. IGBT valves are technically advantageous compared to previous options, as they offer additional grid-support ancillary services (e.g. reactive-power support for connected AC networks and improved power quality control [14]).

1.2. Technical HVAC vs. HVDC Assessment

The use of HVDC transmission over long distances provides several technical advantages when compared to HVAC. DC transmission losses/costs are significantly lower than HVAC due to the absence of transmission line capacitive/reactive charging effects. This limits the main HVDC transmission losses to line-resistive losses, and omits the need for expensive, fast, AC line-reactive compensators [15]. DC transmission can thus be used efficiently for very long transmission distances that exceed 3,000 km as of 2018 [16], compared to 1,049 km for point-to-point HVAC [17, 18]. It also requires fewer cables/conductors and utilizes the full lines transmission capacity up to their thermal limits. This reduces the required cross-sectional area for DC cables and consequently the transmission cost [19]. Right-of-Way (ROW) space (i.e. the required horizontal ground clearance distance) for DC transmission is also considerably lower compared to the AC equivalent, for both overhead and underground bulk power transmission options [20].

Table 1: Technical comparison summary between HVAC and HVDC transmission.

Transmission Type		HVAC	HVDC
Cables/Lines	**Number of Conductors**	Higher (3-phase conductors, lower individual ratings, cumulatively more expensive)	Lower
	Utilization	Limited by skin-effect (although bundled conductors are used to limit it)	Full up to thermal limits
	Losses	Higher (mainly resistive and reactive, requiring expensive line-capacitance compensators)	Lower (mainly resistive and corona losses)
	ROW	Higher (could exceed x3 times of HVDC) [20]	Lower
Maximum Implemented 2018 Distance		Lower (1,049 km: Yuheng-Weifang link in China [17, 18])	Higher (3,324 km: Changji-Guquan link in China [16])
Meshed Grids	**Availability**	Widespread on a global scale	Currently limited with significant predicted growth
	Protective Equipment	Well-Developed UHV Circuit Breakers	Extensive R&D effort to develop HVDC Breakers and/or converters fault blocking capability
Substations	**Cost**	Significantly Lower	Higher (converter stations)
	Losses [21]	Low transformer and HV equipment losses (0.3% in AC double circuit)	Higher station losses (could exceed 1% for VSC)
Economic Viability		UG Cables < 50-100 km Overhead Line < 300-800 km	Beyond HVAC limits (Point-to-Point Links)

Having said that, the expensive rectifier and inverter stations for AC/DC and DC/AC conversion, which are not required in HVAC case, significantly add to the overall HVDC transmission cost. That is, DC transmission fixed cost (stations and equipment) is much higher compared to AC, whereas line costs and losses are highly skewed in the favour of DC. Thus establishing a breakeven distance for both technologies after which DC transmission becomes economically preferable.

The HVDC breakeven distance estimations vary but typical ranges expand between ~300 km to ~800 km for overhead lines and ~50 km to ~100 km for offshore/underground cable links [15, 19, 21, 22]. This variability is related to individual project conditions (e.g. MW/kV rating, transmission terrain and local policies). Table 1 summarizes the main comparison points between HVAC and HVDC transmission, while a more detailed evaluation can be found in [21].

Some applications necessitate the use of reliable HVDC stations as a sole option to link two asynchronous AC power systems in different countries [23] or within the same country, as in Japan (with both 50/60 Hz systems) and the United States (with asynchronous 60 Hz systems) [24-26]. Figure 1.a qualitatively summarizes the cost evolution of HVAC vs. HVDC converters with distance, indicating breakeven points, whereas Figure 1.b provides an example from ABB, comparing the costs of different transmission alternatives for a 6,000 MW/2,000 km link [20].

Collectively, the commissioned; operational HVDC global capacity has well exceeded 200 GW as of 2017, and is expected to surpass 400 GW by 2022 based on announced projects pipeline [27]. Further growth is dependent on market demand and technology development. Figure 2 summarizes the expected cumulative HVDC capacity until 2022.

1.2.1. Conversion of HVAC lines to DC Operation

Due to the technical advantages of HVDC, a conversion of HVAC lines to DC operation might be justifiable (i.e. in terms of expensive HVDC converter stations installation) in cases when a transmission capacity expansion is required, benefiting also from the robust HVDC control schemes that improve the system dynamic response [28]. A transition to DC operation is mainly advantageous in terms of maximizing the conductors' utilization, increasing the transmitted power capacity and decreasing the corona effect compared to AC [29-31]. However, techno-economic analyses are required to assess the different AC uprating techniques such as the use of series AC compensators, Flexible AC Transmission Systems (FACTS) or STATCOM devices against the option of converting to HVDC transmission. Early research works presented and discussed the HVAC to HVDC conversion idea, illustrating the magnitude of potential capacity increment up to 3.5 times by adjusting transmission voltage and conductors' configuration [32]. Conversion to DC operation requires installing HVDC converter stations rated at the full capacity at both ends and may also require the adjustment of transmission tower heads and insulators to accommodate DC requirements. Several methods and case studies have been subsequently presented in literature with variable power capacity increment factors that are dependent on project/transmission configuration [28, 30, 31, 33-35]. The authors of [34] presented a summary of 12 relevant works in literature, including case studies and evaluations of different technical and environmental effects on the conversion feasibility. On the other hand, a CIGRE working group developed a comprehensive guide on AC to DC line conversion including economic and technical constraints, while presenting various case studies such as the conversion of parallel 287 kV AC circuits in the United States to DC operation [28]. Another case study presented in [31] concluded the feasibility of converting a 380 kV double-circuit AC line to hybrid AC/DC operation (i.e. converting one circuit to DC operation), where the power capacity of the converted DC circuit is doubled with a permissible voltage increase by the conductors' limits up to $\pm 450\ kV$.

In terms of practical implementation, it has been reported recently that an AC line of the UltraNet project in Germany has been converted from 380 kV AC to DC, which significantly increased its power transmission capacity. Similar implementations are being studied for various projects where transmission capacity expansion is a requirement [36]. Similarly, AC asset conversion is taking place in a pilot project "Angle-DC" in Wales by ScottishPower to convert a 33 kV AC line into ±27 kV Medium-Voltage DC operation with a similar goal of maximizing the line capacity in response to the surging electricity demand [37]. This introductory section serves to illustrate the potential and capabilities of DC transmission as a serious competitor to AC transmission in various applications.

1.3. Contributions and Scope

Several HVDC reviews have been published in literature, targeting different aspects of the technology adoption. A significant number of reviews focus on individual system components (e.g. converter stations, cables and protection equipment) [10, 38-40], while others provide detailed system-level comparison with other transmission alternatives (e.g. VSC and LCC based HVDC, or HVDC vs. HVAC) [21, 41, 42]. In addition, other reviews target implementation outlook and challenges for HVDC technologies within a geographic/policy based context [15, 43, 44].

However, a comprehensive market study and technical review has not yet been fully addressed to the best of authors' knowledge. In addition to an updated, detailed, step-by-step overview of HVDC technology and outlook on a global scale that combines both utility and academic experiences. This paper thus presents a high-level assessment of the available technologies, starting from individual components to system level analysis, while providing relevant and carefully selected case studies from different international markets. The paper also demonstrates the role of HVDC in achieving RES targets. Collectively, the present paper cites 248 works from literature, 75% of which were published during the past 5 years.

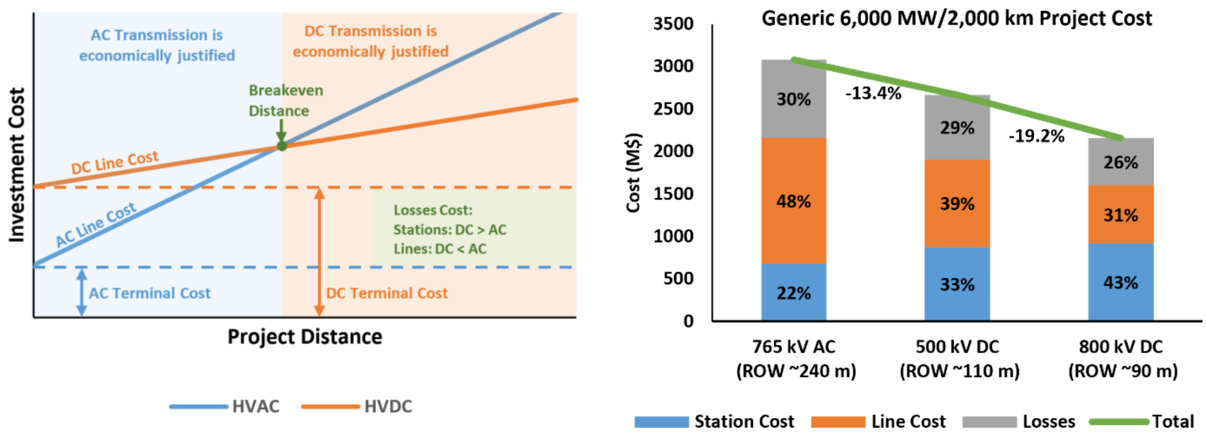
The main contributions of this paper are summarized as below, where Figure 3 graphically presents the logical sequence followed in this work.

a) Comprehensive review of HVDC systems drawn from real projects and authors critical assessment of existing literature based on their expertise.
b) Highlights of contemporary technical and economic challenges of HVDC transmission systems.
c) Comprehensive summary of market data, costs, and statistics for individual system components and overall structures.

The rest of this paper is organized as follows: Main HVDC market trends in terms of global capacity distribution and technology supplier landscape are first discussed and analysed in Section 2, which gives important understanding of the market dynamics and global demand variation.

Section 3 presents an overview of the main HVDC transmission system components and a detailed assessment of the state-of-the-art technologies, including a summary of system-level control algorithms. This section is concluded by technical and economic comparisons between different competing HVDC technologies with relevant case studies.

Section 4 summarizes the main contemporary system-level challenges to the HVDC transmission market, focusing on network operation and technology requirements. Section 5 then highlights the HVDC technology outlook and the required development areas to overcome existing technical and operational challenges, with a summary of literature and expert predictions for development limits by the end of next decade. The overall growth factors of HV interconnectors are also analysed in this section, driven by supportive cross-jurisdiction interconnection policies and the anticipated large-scale distant onshore and offshore renewable energy expansion to meet the national renewable energy integration targets. Finally, the manuscript sections are summarized by concluding remarks.



(a) (b)

Figure 1: HVAC vs. HVDC cost comparison: (a) qualitative breakeven distance assessment. (b) cost and ROW estimation for a 6,000 MW transmission for 2,000 km [20].

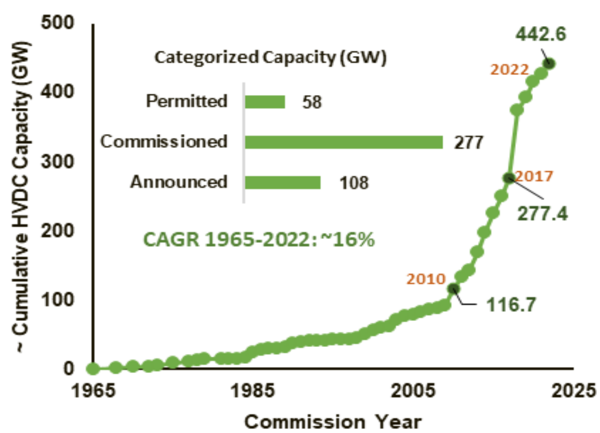


Figure 2: Capacity evolution of HVDC interconnectors based on BNEF raw dataset [27].

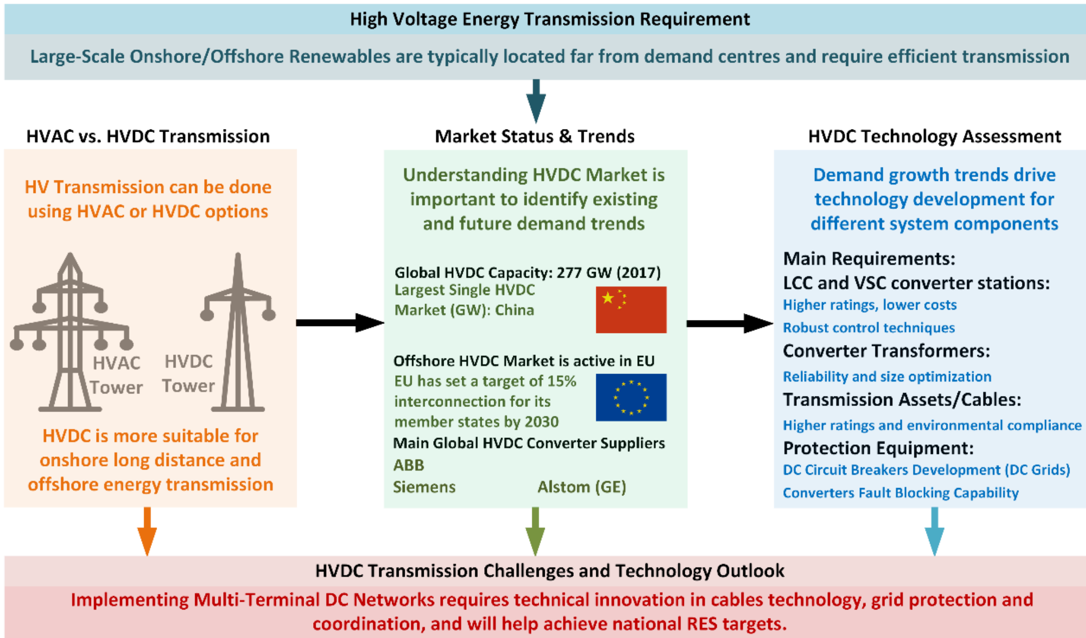


Figure 3: Summary of the topics covered by this paper and the contribution of HVDC interconnectors adoption in serving the global renewable energy expansion landscape.

2. HVDC Market Overview

This section presents a detailed review of HVDC transmission market status and trends in terms of capacity evolvement, geographic/demand distribution and leading system manufacturers/vendors. The following statistical analysis is mainly based on a raw dataset released by BNEF in February 2016. The analysis covers operational worldwide projects that are commissioned since 1965, and spans to cover pipeline projects until 2022 that were announced up until the dataset release [27]. This dataset underwent a filtration process excluding decommissioned, abandoned projects, in addition to adjusting some inconsistent entries by the authors and adding a number of projects that were missing using other literature and manufacturers sources, which are cited where needed. The reviewed dataset consists of 252 considered projects that are either commissioned, announced or permitted/under construction. Several subsets of the available data are considered hereafter in this paper based on data type availability (e.g. 170 of the 252 projects had data relevant to suppliers/manufacturers). The use of any subset in this paper is clearly mentioned in order to provide the reader with a reference sample number to the illustrated comparisons. The numbers presented are thus indicative of global trends but do not provide an absolute measure due to the described subsets utilization.

2.1. HVDC Geographical Landscape

As Figure 2 illustrates, the total expected HVDC transmission capacity operational by 2022 surpasses 400 GW. More than half of this capacity (~52%) is internal in Asia (i.e. both sending and receiving ends are located in Asia). This market domination is mainly influenced by China and then India as key market players. Many HVDC projects in that area are constructed to transmit bulk energy from distant generation sites/renewable energy sources to major load centres over very long distances due to the vast geographic sparsity of these countries. Several recent projects in China are highly rated at 6,400 MW/±800 kV [2, 13, 27, 45], with some links already exceeding 10,000 MW [16, 46]. This development has pushed the limits of available technologies and encouraged manufacturers to invest in higher-rating equipment and testing facilities. For instance, main HVDC suppliers (ABB & Siemens) have recently announced their new 1,100 kV single-phase transformer units for Ultra HVDC (UHVDC) applications [47, 48].

Based on [27] dataset analysis, it is estimated that the average capacity for internal Asian projects is around 4,000 MW, which is significantly ahead of other regions (e.g. 1,600 MW for Central & South America, compared to 1,500 MW for North America and around 1,100 MW in Europe). The evolving Chinese dominance in particular over the global HVDC capacity is evident in Figure 4, which illustrates the main markets share between 2010-2017. Similar trends are persistent over longer periods; though graphical illustration is presented for this period in particular due to its contribution to the rapid HVDC expansion presented by Figure 2, especially in China [2] .

The largest number of recorded projects lays in Europe. Yet the internal European projects capacity accounts for 22% of global HVDC projects compared to the Asian capacity dominance illustrated earlier due to the demand distribution and geographical variations. That is, constructing expensive UHVDC links with very high transmission capacities is only justified when there is a matching demand in importing areas. In this context, the moderate average capacity of European HVDC links compared to that of China is reasonable, considering the absence of the need case for very high power transfer or very long distance links. Instead, cross-borders point-to-point HVDC links with 1-2 GW capacity are common in Europe as part of EU incentives and initiatives to increase the interconnection of markets and security of supply [15, 39].

In fact, several HVDC links are supported both financially and regulatory by the EU under the "Projects of Common Interest" pillar with several defined priority energy corridors such as the "Priority Corridor Northern Seas Offshore Grid" and "Priority Corridor Baltic Energy Market Interconnection Plan". These plans, including both onshore and offshore projects, serve the EU target of achieving its energy interconnection capacity target of 15% (relative to the member states installed capacity) by 2030 [7, 49, 50], while supporting broader utilization of available, sparse, renewable energy sources. Some European countries have already exceeded this target by 2014. Namely, Austria (29%) and Belgium (17%) [7]. This European trend for interconnection of electricity markets is intended to help facilitate proposed plans to reduce nuclear and thermal based generation and to replace it with renewable energy, mainly offshore wind and PV [15].

A correlation can also be observed between the discussed geographic capacity rating distribution and the transmission DC voltage as higher power is transmitted more efficiently at higher voltages [21]. Asia has the highest average transmission voltage as many of its established HVDC links since 2010 are rated at ±800 kV, and lately up to ±1,100 kV using overhead transmission lines. Brazil has also recently inaugurated its first ±800 kV HVDC system for +2,000 km point-to-point power transmission at Belo Monte [51]. On the other hand, the maximum DC transmission voltage at any other location is currently limited to ±600 kV due to the moderate power rating and distance of the implemented projects. Figure 5 summarizes the average and maximum HVDC transmission voltages at different continents, and compares these numbers to the average power rating per area.

Finally, Figure 6 shows a world map summarizing most of the existing and some planned HVDC links based on data from the European Joint Research Centre released in 2017 [52]. Some planned projects are missing from the map (e.g. the Biscay Gulf interconnector between Spain and France [53]), yet it reflects the generic landscape of HVDC transmission geographic distribution.

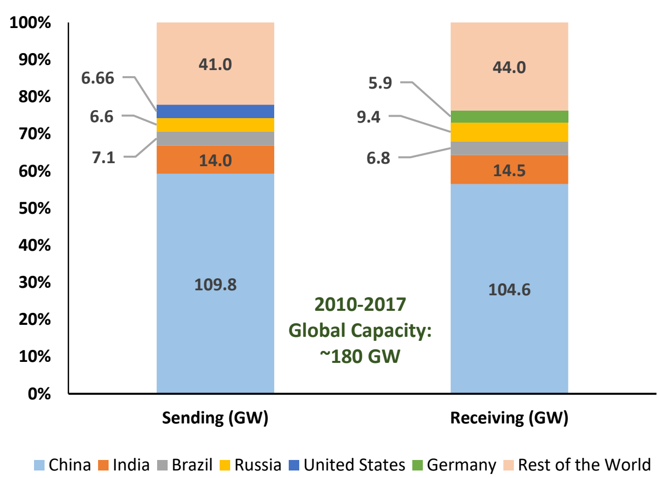


Figure 4: HVDC global capacity distribution between 2010 and 2017, based on [27] raw dataset.

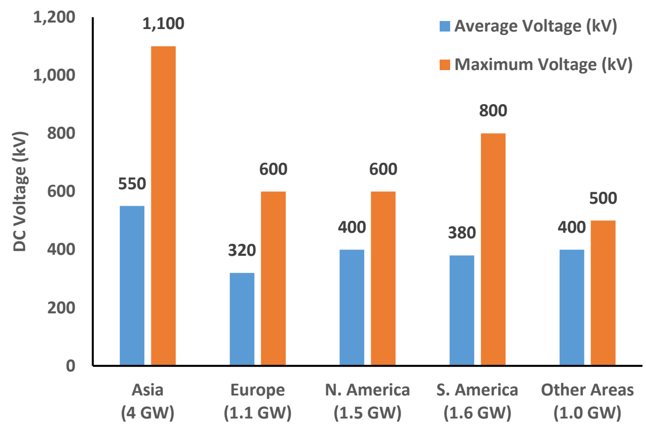


Figure 5: Global Distribution of HVDC Transmission Voltage with (average power per area), based on [27] raw dataset and [51] .

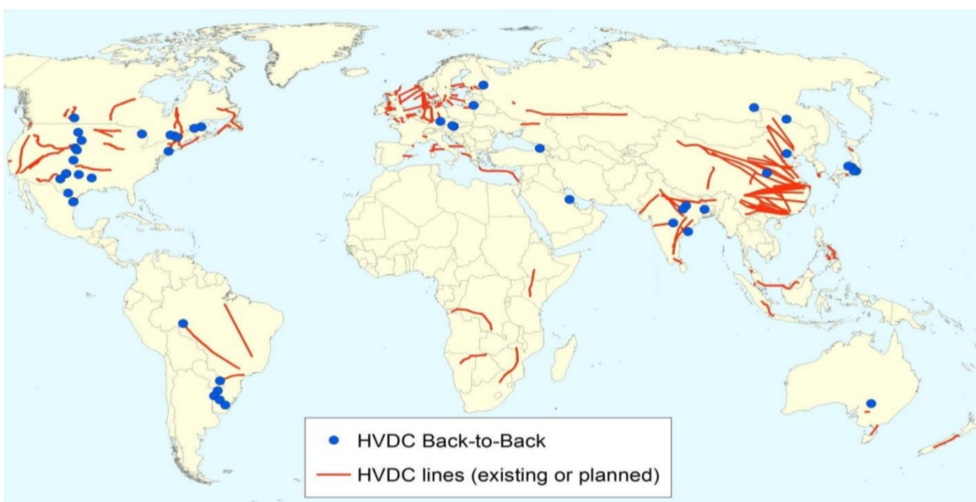


Figure 6: Global HVDC capacity distribution overview as of 2017 [52].

2.2. Main HVDC Converter Suppliers

The first commercial HVDC link was commissioned by ABB more than 60 years ago using Line Commutated Converter (LCC) technology [13]. After more than 60 years, the HVDC converters market is still dominated by three suppliers: ABB, Siemens and Alstom Grid whose energy business was recently acquired by General Electric (GE) in 2015. The following statistics are based on a subset of 170/252 projects from the BNEF dataset with available suppliers' data [27]. Missing project data is not concentrated in a single geographic location which ensures the presented conclusions give a valid indicative representation of global trends, if not a definitive absolute measure. This analysis aims to identify main HVDC market contributors and the distribution of their activities in terms of geography and technology adoption to provide the reader with a technical context of the global HVDC scene.

Figure 7 presents the main suppliers-based statistics, where the term *ABB/Siemens or GE Lead* indicates the existence of multiple suppliers in a project. That is to say, classifying a project as ABB, Siemens or GE lead does not mean that the other two or even other suppliers are not present in this particular project, rather, the classification aims to simplify the suppliers' landscape analysis as allowed by the available data.

Being a mature technology used for decades and more suitable for overhead high-power transmissions [8, 54], the number of LCC based projects is significantly higher than their VSC counterparts. Although the latter provides more technical advantages. Further technical discussion on converters technology is presented in Section 3. Figure 7(b) summarizes the technology based suppliers' comparison, based on the same available BNEF data from 170 projects, where N/G indicates missing technology information.

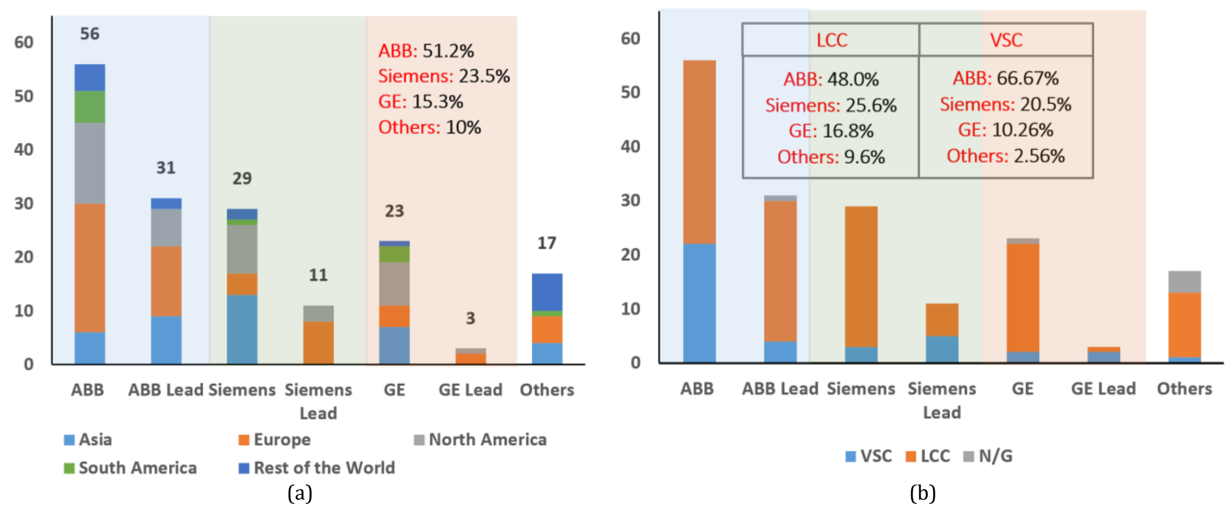


Figure 7: Global HVDC technology suppliers landscape based on: (a) geographic distribution, (b) converter stations technology. Data: [27] based on 170/252 HVDC projects sample.

3. HVDC Technology Assessment

This section provides detailed assessment of the available HVDC transmission technologies by first introducing typical HVDC system structure, followed by a specific review of each component within the system. Namely, the section covers converter stations, converter transformers, transmission options as well as a summary of control schemes and protection equipment. Relevant case studies discussing the design alternatives from two real HVDC projects are also presented. It is important to note that the equipment footprint, distribution and proportions vary significantly with rating/technology. Thus, a generic HVDC structure overview is presented in Figure 8, while briefly summarizing main system components with their available technologies and status.

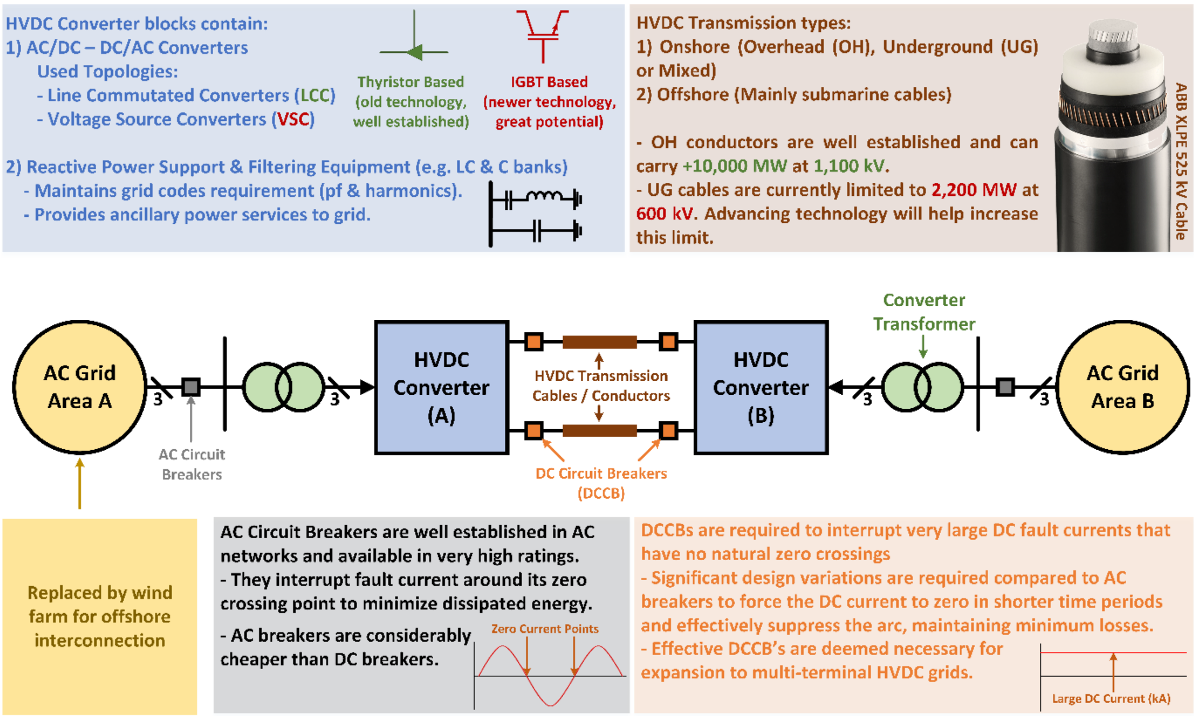


Figure 8: Generic HVDC transmission project layout with component-based description. DCCBs are not typically implemented in point-to-point links, and are displayed to illustrate their principal of operation.

3.1. Converter Stations

The backbone of any HVDC project is the converter station as it converts AC voltage to adequate DC transmission voltage level (AC/DC converter) at one end, and converts the DC voltage back to adequate AC grid interfacing voltage level (DC/AC converter) at the other end. The notion of sending and receiving end are often used interchangeably depending on the power flow direction [55]. Two main converter types are being used in HVDC links: Line Commutated Converters (LCCs) and Voltage Source Converters (VSCs). Both are discussed below in terms of technology overview, required auxiliary equipment (i.e. filters and reactive compensators), available ratings and their economical, technical viability.

3.1.1. Line-Commutated Converters

LCC converters, as the name implies, are operated based on the AC transmission line parameters. Their switching frequency matches the line frequency (50-60 Hz). Gate control signals are used to direct their operating (i.e. rectifier/inverter) mode based on thyristor firing angles (ideally: $0 - 90°$ for rectifier and $90 - 180°$ for inverter mode), as well as for power quality regulation [56, 57].

As a result, LCCs lack AC faults ride through capability and have no inherent black-start capability. That is, they cannot be used to restart a blacked-out AC systems connected to their terminals since thyristor operation is dependent on line frequency voltages which will not exist in case of a black-out. To overcome this limitation, the first HVDC link in Gotland used auxiliary synchronous condensers powered separately to restore the HVDC converter operation in case of an AC fault, which in turn could participate in restoring AC system operation [58], adding to the system cost and complexity. Different research works have evaluated the technical requirements and possible control techniques for successful participation of LCC stations in AC systems black-start [59, 60].

3.1.1.1. Technical LCC Assessment

Conventional LCC stations utilized 6-pulse thyristor bridges shown in Figure 9(a). The converter operation depends on the thyristor firing sequence to produce a unipolar DC voltage and current outputs. The 6-pulse cyclic DC output is smoothed by the DC reactor connected at the DC output side, with the aid of additional DC filters to ensure power quality requirements are met. The smoothing reactor is rated for full converter current (increasing its size) and is used additionally to mitigate abrupt current variations, prevent commutation failure (CF) and maintain DC current continuity during light loading conditions [61]. The term CF refers to the failure of DC current to commutate from the outgoing thyristor to the incoming thyristor when the AC voltage distortions in the host AC grid affect the firing sequence of the converter valves. CF leads to simultaneous conduction of more than two thyristors and sudden drop in the DC voltage or even creation of DC short circuit across the link.

In contrast, Figure 9(b) shows a high-level block diagram of the more common 12-pulse LCC converters, consisting of two series connected 6-pulse units fed separately by Y-Y and Y-Δ transformers to create a required 30° phase-shift for commutation [56]. Advantages of 12-pulse converters include their enhanced reliability, reduced harmonic currents in AC and DC sides and filtering requirements. Typical power loss in each LCC station are ranging from 0.6% to 0.8% [15, 21, 54]. Detailed discussion and derivations of LCC operation principle is found in [56, 57, 61].

LCCs are classified as Current Source Converters (CSC) as they permit DC current flow in one direction. Power-flow-reversal thus necessitates reversing the DC voltage polarity at both converter stations (i.e. shifting between inverter/rectifier modes). This process creates significant DC stress levels on transmission and station equipment that could damage some cable types as discussed later. Yet, this occasionally does not pose a major limitation since power-flow reversal is often not required as in case of HVDC transmission from distant generators to load centres.

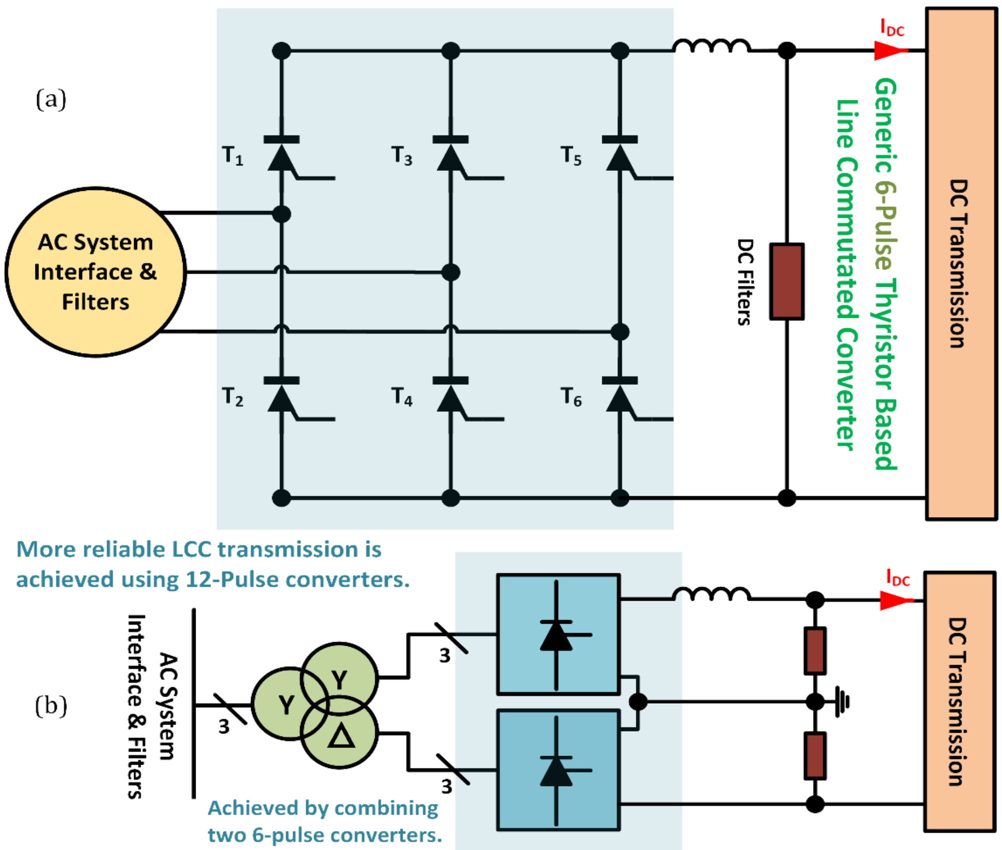


Figure 9: Typical Line-Commutated Converters Topology: (a) 6-Pulse bridge converter, (b) 12-Pulse bridge converter.

That is, high-Power LCC transmission often links generation areas with higher inertia and short-circuit level to receiving load centres that could be substantially weaker due to their lack of rotating machines [46, 62]. Connecting receiving LCC stations to weak AC networks can cause significant problems (e.g. commutation failure). A network short-circuit ratio (SCR) is widely used in power systems to characterize the strength of AC grids. This parameter is traditionally defined as the ratio between a network's three-phase short circuit fault level (SCL) at the point-of-common-coupling (PCC) to the rated DC power of the HVDC [63, 64]. IEEE standard 1204-1997 classified an AC grid as weak if its SCR < 3, and very weak when SCR < 2 [65]. Other recent works investigated various limits and definitions of the SCR and other assessment parameters to accommodate emerging multi-terminal and multi-fed HVDC systems [63, 66].

Another major disadvantage of LCC converters is their inherent consumption of around 50% to 60% of their operational MW as reactive power. This is due to the inherent delay of their current waveforms with respect to commutation voltage. Necessitating the operation of additional, expensive, reactive AC compensation equipment [56, 67, 68].

Overall, LCC projects still dominate the HVDC market as indicated by Figure 7(b). The technology is well established despite the abovementioned design challenges. Combinations of LCC converter stations currently provide the highest available ratings and power transfer capabilities in HVDC market, recently achieving 12,000 MW/±1100 kV in China with the Changji-Guquan link [16, 47]. Different LCC design variations have also been proposed over time to mitigate the described limitations, including Capacitor Commutated Converters (CCCs). This type of converter is briefly discussed in the following subsection.

3.1.1.2. *Capacitor Commutated Converters*

LCC stations connected to weak AC grids are more prone to commutation failures that can lead to significant power loss. Thus, the CCC configuration has been proposed and successfully implemented by installing series capacitor modules between converter transformers and the inverter thyristor valves. This modification reduces the effective stations reactive power consumption seen by the AC side (down to 10-15% [69]) and consequently increases the power factor, reduces reactive AC shunt requirements and mitigates the chance of commutation failures [70]. The Brazil-Argentina Back-to-Back HVDC interconnector with a total capacity of 2,200 MW is the main example. ABB used this technology to compensate for reactive power and avoid building an additional synchronous compensator [71]. Though, large-scale implementation of CCC requires complex control to balance capacitor voltages and achieve stable operation. Practically, CCCs are implemented in a limited number of projects, because conventional CCC schemes are challenging in terms of: i) demonstrating undesired transient response after unbalanced faults. ii) requiring additional arresters to limit their charge in case of abnormal operation; and iii) increasing the voltage stress on the thyristor valves, which can reach up to 2 or 3 p.u. [70, 72, 73]. Finally, researchers are actively attempting to address these challenges by proposing different dynamically controlled-capacitors using active modules (e.g. the Thyristor-Controlled-Series-Capacitor, TCSC) to replace the conventional fixed capacitors with promising potential [70, 72, 74].

3.1.2. *Voltage-Source Converters*

The first implementation of VSC converters technology in HVDC transmission was in 1997, using IGBT valves for the 3-MW Hällsjön-Grängesberg test link in Sweden by ABB [13]. Since then, VSC technology has improved significantly and proven itself as a key market competitor that has been gradually replacing LCC options especially in offshore applications and power transmission projects with ratings of less than 2,000 MW (highest operational VSC rating). A recent study published by BNEF reported that the share of VSC technology from the total number of new projects could approach 65% by next decade [75].

3.1.2.1. Technical VSC Assessment

The shift towards VSC technology is expected to continue due to its technical superiority and gradual ratings development. VSCs are self-commutated, operable in 4-quadrants, and do not depend on line voltages, rather, they rely on external control voltage signals for commutation [41, 76]. Power-flow reversal in VSC stations is based on reversing the DC current direction while its voltage polarity remains constant , which is much faster and reliable compared to LCC [77]. These features are advantageous in terms of establishing the VSC ability to:

- Utilize advanced switching techniques (e.g. Pulse-Width-Modulation (PWM) [78]), allowing for switching frequencies in the lower KHz range [79, 80]. This significantly reduces the harmonic filters sizing requirements by moving the main distortion frequency component away from the baseband (50-60 Hz) and leads to a significant reduction in reactive equipment and footprint costs compared to LCC.
- Ride through symmetrical and asymmetrical AC network faults and offer post-fault black-start to the host AC networks, which allows the converter to initiate the restoration of rated AC network voltage in a post-black out scenario. Several VSC black-start implementation setups and relevant control techniques are discussed in [58, 81, 82].
- Independently control active and reactive power consumption/generation. This makes it possible to support the AC grid power quality (i.e. converter stations can even act as independent STATCOMs during DC transmission line outages, or can provide reactive power support while transmitting active DC power)) [14, 76].

The basic structure of VSC stations (two-level arrangement) is shown in Figure 10. Different configurations of the two-level arrangement are employed in existing links. For instance, conventional two-level (C2L) converters that utilize series/parallel strings of IGBT valves in a similar configuration to thyristor-based 6-pulse converters [13]. Modified topologies have later emerged and are widely adopted in recent projects. For instance, Siemens has launched its HVDC Plus scheme which utilizes VSC based Modular Multilevel Converters (MMC) as its core technology [83, 84]. The NEMO interconnector, commissioned in early 2019, also uses HVDC Plus converters (with MMC).

3.1.2.2. Modular Multilevel Converters

The technical operating principle of MMC technology relies on replacing switching series semiconductor strings with equivalent IGBT/capacitors submodules (SMs) that provide enhanced operation quality with a high scalability/flexibility factor, in addition to increasing the converter station fault tolerant operation. The basic arrangement of Half-Bridge (HB) MMC is also illustrated in Figure 10 which highlights the main differences as compared to C2L-VSCs. An increase in the number of SMs permits the MMC to generate sinusoidal AC voltages with practically negligible harmonics, thus reducing or even eliminating the need for AC and DC filtering (when very large number of levels is used) [85].

MMCs also decrease the submodules voltage/current stress, while reducing switching losses and filtering requirements compared to other VSC topologies by effectively distributing the main bulky DC link capacitors into smaller units embedded to the submodules, (see Figure 10) [41]. Qualitatively, the advantages of MMC-VSC can be summarized as: 1) modularity and scalability. 2) high-efficiency. 3) superior harmonics performance with increased number of SMs per arm [42]. Some existing and operational MMC-HVDC projects are: Trans Bay Cable (400 MW/±200 kV, USA, 2010) and INELFE (2x1000 MW/±320 kV, France-Spain, 2015) [86].

It is expected for MMCs to dominate the VSC-HVDC landscape as the technology advances further. At present, MMCs are the preferred industry choice for VSC-HVDC with stations power rating of up to 1,000 MW [87]. A published report on HVDC economics highlights that the economic case for MMCs is currently better when compared to conventional VSC converters in several cases [88]. However, the reliability of MMC based systems is still an active research area due to the large number of components involved [89]. Accordingly, extensive research efforts are underway to increase MMC efficiency and reliability through innovative topologies and control algorithms that use different modular cell structure (e.g. Half vs. Full Bridge) [87, 90-92]. The implementation of MMCs in several VSC-MTDC network configurations is also preferable due to their potential fault-blocking capabilities [78, 93]. In fact, several Multi-Terminal MMC-VSC projects are either commissioned or under-construction in China as illustrated in Table 2, with the largest being the Zhangbei four-terminal DC grid (4,500 MW/±500 kV) that aims to meet the expected higher demand during Beijing 2022 Winter Olympic Games [94].

Table 2: List of some existing and planned Multi-Terminal MMC-VSC Projects in China

System Name	Terminals	Rated Power (MW)	Rated MTDC Voltage (kV)	Status
Nan'ao [95, 96]	3	200/100/50	±160	Commissioned (2013)
Zhoushan [97]	5	400/300/100/100/100	±200	Commissioned (2014)
Zhangbei [94, 98]	4	3,000/3,000/1,500/1,500	±500	Under Construction

The possible use of Integrated Gate-Commutated Thyristor (IGCT) valves in future MMC implementations also has a significant potential due to their higher ratings and reliability. The lifecycle cost of IGCT compared to IGBT for HVDC applications is estimated to be less in [99], which also presents an interesting comparison between the two switching devices for MMC.

Currently, VSC-HVDC station losses vary based on the adopted topology, with a typical magnitude of 1% per station (varies depending on the topology and switching frequency, and estimated to be less by some recent sources [54]). Notably, it is predicted that new MMC station losses could approach LCC losses range by 2020. It is also important to note that different variations to the discussed topologies exist and could be utilized on an application specific basis.

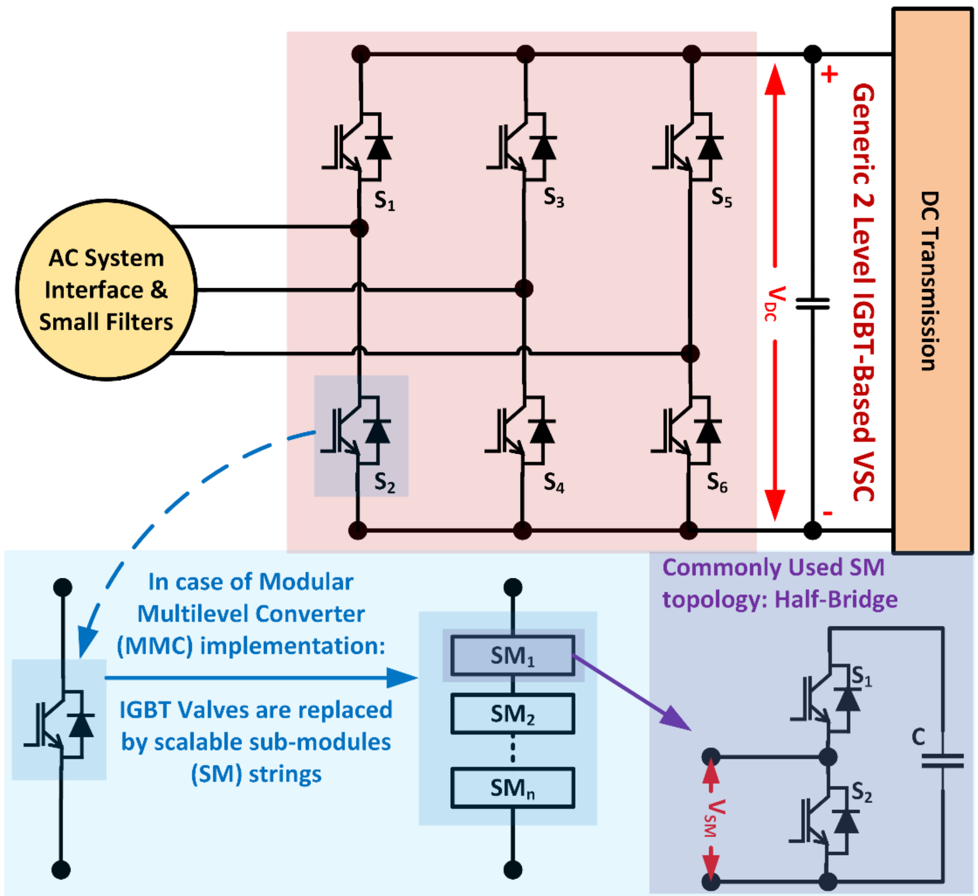


Figure 10: Basic structure of VSC converter station, showing generic two-level topology and the advanced Modular Multilevel Converter (MMC) with Half-Bridge cell modules.

3.1.3. *LCC vs. VSC Comparison*

After reviewing the main features of HVDC converter technologies, the LCC and VSC options are compared in terms of their main technical and economic parameters. Although the current market share of VSC considerably lags the LCC technology, the expected trend is for VSC share to increase further as the technology advances and allows for higher ratings at reasonable cost that justifies its added technical capabilities [80]. NEMO interconnector is an example, where initial project planning in 2008 considered using LCC technology since VSC alternatives were not tested for higher power ratings, such as 1,000 MW. Yet the consequent VSC development shifted the adopted technology to MMC-VSC [100].

Further, VSC technology is more suitable for DC grids implementation based on its constant DC voltage behaviour and control advantages [78, 101, 102]. Unlike the current-source based LCCs that have limited applicability in multi-terminal DC (MTDC) grids because reversing power flow direction at any connected station would require reversing the voltage polarity for all the other connected DC stations [40]. The role of LCC technology in MTDC implementation is thus mainly restricted to hybrid applications that aim to facilitate the integration of large LCC assets into VSC based DC grids [103, 104]. In contrast, conventional VSC stations also have smaller physical footprint compared to a similarly rated LCC station by 40-50% [75].

The present moderate implementation limit of 2,000 MW for VSC based project is mainly justified by the stations significant cost increase beyond this point compared to the well-established LCC technology as illustrated by Figure 11, which is based on a UK transmission dataset from 2015 [105]. This cost dataset source is selected as it is classified in [106, 107] to provide the least deviation from real costs when used for HVDC cost modelling. It is important to note that converter stations cost is variable and project dependent, yet the presented sample data accurately reflects the described trend. The sharp cost increment of VSC stations is explained by the moderate maximum available IGBT voltage/current ratings. Data from recent ABB releases [108] show that their high voltage IGBT modules rating ranges from 1,700 V to 6,500 V. The highest current withstanding capability is attributed to the 4,500 V IGBT modules, justifying their common use in HVDC. In contrast, thyristors are readily available at higher ratings: (1,600 V to 8,500 V per module with currents between 350 A and 6,100 A) [108].

For ease of illustration, assume a hypothetical converter rated for 400 kV DC link voltage and 800 MW rated DC power, which can be realized by two-level VSC or LCC. With typical commercially available semiconductor devices such as 4.5 kV/3 kA IGBT and 8 kV/4 kA thyristors, and device voltage utilization of 60% for increased reliability and account for potential system over-voltages [109]. Based on the selected parameters, it is estimated that the number of required IGBTs is 894 compared to 504 thyristors only. Further, the number of switches is effectively doubled if current flow requirements are increased beyond a single-module capability. Thus, different combinations result in different device count and unit cost, and these are indicative parameters for the overall station cost. In the case of MMC converters, the increased number of balancing capacitors may also escalate the overall station cost.

In contrast, the technical feasibility of accommodating 8,000 MW DC power at a single point of an AC grid through LCC-HVDC is challenging for many existing power grids in the world, including Europe (e.g., for SCR = 2, the required three-phase short-circuit level at the PCC will be 16,000 MVA). Whereas futuristic VSC-HVDC links of such rating are more capable of connecting to weak networks. Finally, Table 3 summarizes the main comparison points between both LCC and VSC technologies in HVDC applications.

3.1.3.1. Hybrid LCC-VSC HVDC Systems

Several recent research works are investigating a hybrid LCC & VSC operation in HVDC links. The main objective of such schemes is to utilize the advantages of both converter technologies. For instance, connecting LCC station at the bulk generation site to make use of its reduced cost and high capacity, while connecting a single or multiple VSC station at the receiving side to exploit the reduced footprint of VSC stations and to utilize their ability to support weak grids and overcome potential commutation failure [110-112]. In such hybrid systems, bidirectional power flow is not typically needed, and LCC terminals mostly operate in rectifier mode while VSC terminals operate as inverters. Yet, the use of intermediate DC-DC transformers between VSC and LCC stations through hybrid configurations such as the Active-Forced-Commutated Bridge is investigated in [113] to sustain effective bidirectional power flow in hybrid HVDC links when the LCC voltage polarity is reversed, with the capability of stations voltage matching.

Other hybrid VSC and LCC connections within the same converter station are discussed in literature. The authors of [114] analysed four hybrid configurations in terms of their combined power rating and PQ capability enhancement as compared to conventional LCC stations. Hybrid multi-infeed systems are also investigated in [115], where parallel, independent, VSC and LCC DC lines are connected to the same AC bus to improve its voltage stability.

At present, a number of hybrid LCC-VSC HVDC links are reported by [115] to be in the planning phase in China. Namely, the hybrid Baihetan-Jiangsu 8,000 MW link in China, which is characterized by a conventional LCC station at one end, and a hybrid LCC-VSC station at the other end. The 3-terminals Wudongde-Yunnan HVDC link is another interesting hybrid link being considered for practical implementation, utilizing an 8000 MW LCC station at the sending end to benefit from the high LCC capacity and lower scaled cost, while using VSC stations of lower rating at the receiving areas with 5000 MW and 3000 MW, respectively [110, 115, 116].

Table 3: Comparison between HVDC transmission technology options

HVDC Converter Types		LCC	VSC
Switching Device		Mercury Arc (1950s – 1970s)	IGBT (1990s – Present)
		Thyristor (1970s – Present)	
Commutation (Frequency Range)		Line Dependent (50-60 Hz)	Self-Commutated (up to few kHz)
Station Power Loss [15, 54, 117]		0.6%-0.8%	~ 1%
Power-Flow Reversal Mechanism		Voltage Polarity Reversal (slow, causes more current stress)	Current Direction Reversal (Fast, adds more reliability)
Network Strength Dependency		Dependent (expensive added equipment in weak grids) [58]	Largely Independent
Converter Station Footprint		Larger	Smaller (40-50%) [75]
Inherent VAR Consumption		50-60% of rated MW	None, and can support reactive power to AC grid
Reactive/Filtering Equipment Requirements		High (Expensive)	Low
Inherent VAR control and Grid Support		No	Yes
Inherent AC Grid Black-Start Capability		No	Yes
Fault Handling Capability	AC Side	Lower (Line-Frequency Dependent)	Higher (MVAR Support/Black Start)
	DC Side	Higher (DC Reactor/SC failure)	Lower (High di/dt rate)
AC & DC Side Harmonics Level		Higher	Lower
Market Share (# of Projects) [27]	(1954-2018)	81%	19%
	(2010-2018)	70%	30%
Available Rating Combinations*	Max	12,000 MW/ ±1,100 KV	2,000 MW [118]/ ±500 kV [15] (525 kV [119]*)
	Average	2,000 MW/ ±400 kV	580 MW/ ±220 kV
Common Applications		High-Power, Long Distance	Offshore/Cable-based Projects
Multi-Terminal HVDC Suitability		Limited	Highly Suitable
Stations Cost (at High Ratings)		Lower	Higher

*Current maximum VSC voltage is ±500 kV at Skagerrak 4 project [15], which will be taken over by NordLink in 2020 with ±525 KV [119].

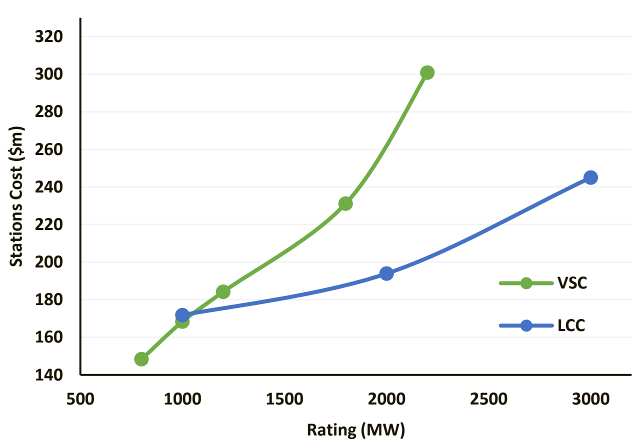


Figure 11: LCC and VSC stations cost evolution with rating based on actual data from [105].

3.1.4. Evaluation of HVDC Transmission Configurations

Both LCC and VSC links can be connected using different network configurations. The DC network topology or configuration selection is mainly influenced by the required level of reliability, rating, cost-effectiveness and complying with local policies and regulations [120]. Commonly used topologies of HVDC transmission systems are DC mono-pole and DC bi-pole, while DC tri-poles are rarely implemented and are mostly based on design variations of the other common configurations [121]. In contrast, Back-to-Back (B2B) connections are primarily used to link unsynchronized neighbouring AC networks. One such example is Al-Fadhili project, commissioned in 2009 to link Saudi Arabia system to its neighbouring markets (Kuwait, Qatar and Bahrain) with a total capacity of 1,800 MW [122].

Another subset of the BNEF dataset [27] consisting of 160/252 projects with available configuration data reveals that 33% of them are configured in a B2B fashion. Signifying the important role of this configuration in networks interconnection. Most of these B2B links are connected using LCC converters (94% of the considered projects within the subset) compared to limited number of VSC links since LCC stations have less power loss. Yet, several research works discuss different efficient VSC B2B configurations and control techniques mainly based on MMC topologies [23, 123].

3.1.4.1. Monopolar Configurations

Power transfer between the two converter stations in this configuration utilizes a single DC pole rated for full high-voltage DC capacity. The return circuit can be a low voltage return path (asymmetrical monopole), which may be realized using an earth electrode at each station, or a low-voltage metallic return link [124]. Earth electrodes require special design considerations to accommodate the fully rated DC current (in kA), and are typically placed away from the converter stations and connected using electrode lines [125, 126]. This option is cost effective and avoids the use of return cable/conductor extending over the whole link distance. Yet, several existing regulations/policies restrict the use of earth electrodes in many HVDC projects due to their negative environmental impacts, especially in case of buried cables underground or subsea: potentially causing corrosion to nearby pipes and affecting sea creatures in the latter case [126]. When used, the metallic return link is rated for full current, but with significantly less voltage insulation requirements compared to the HV line as it's placed in the low voltage path. Figure 12(a) illustrates both conventional HVDC monopole connection options, which are applicable to both LCC and VSC projects, but more commonly used with LCC.

Another monopole configuration that equally shares the full rated HV between two positive and negative links connecting both stations is known as symmetrical monopole (e.g. ±320 kV lines rather than single 640 kV line to ground) [124]. The direct advantage in symmetrical monopole systems is decreasing the rating of the links, which is especially important when underground/subsea cables are used due to their currently available moderate voltage ratings compared to the overhead (OH) lines. Figure 12(b) illustrates the symmetrical monopole configuration, where midpoint grounds are defined at both converter stations. This configuration is common for offshore VSC applications. On the other hand, it is rarely implemented in case of LCC, with the NorNed link as an exception, where each station has a single 12-pulse converter configured to produce opposite transmission polarities [127].

The main disadvantage of the discussed monopole configurations remains in that there is no inherent redundancy in the design, meaning that when there is a fault in one of the lines or converters, then the full transmission capacity is lost [128].

3.1.4.2. Bipolar Configurations

This configuration is the most widely used in HVDC transmission as it commonly provides increased reliability. Figure 12(c) illustrates a high-level block diagram of bipolar configuration alternatives, where each station contains two converters grounded at midpoint. These converters produce equal and opposite HV outputs, creating a normal energy flow path at the outer loop with negligible flow in the neutral/earth connection. The mid-point emergency return path can be designed using either earth electrodes or metallic return link, similar to the monopole case.

The main advantage of common bipolar configurations is the increased reliability, which is analogous to a double-circuit AC transmission line. That is, a fault on any single transmission line/cable or converter pole causes only that link to independently shut down. In this scenario, provided that the fault does not affect the other pole assets, the neutral link is used as a low voltage return path allowing for continued operation up to 50% of the total HVDC power capacity [21, 67]. The inherent voltage reduction discussed for symmetrical monopoles is also a key parameter for bipolar links to increase their power transfer capability.

On the other hand, the rigid bipolar configuration is sometimes used for long distance transmission. In this configuration, no return electrode (for environmental compliance) or return conductor (for economic consideration) are used. Indicating a 100% power loss in case of a single cable fault, or a 50% power loss in case of single-pole converter fault with proper current re-routing [129].

Collectively, 53% of considered dataset projects utilize bipolar links (79% without Back-to-Back projects). Figure 13 summarizes the share of each HVDC configuration in the HVDC market based on a 160 project subset from the BNEF data [27].

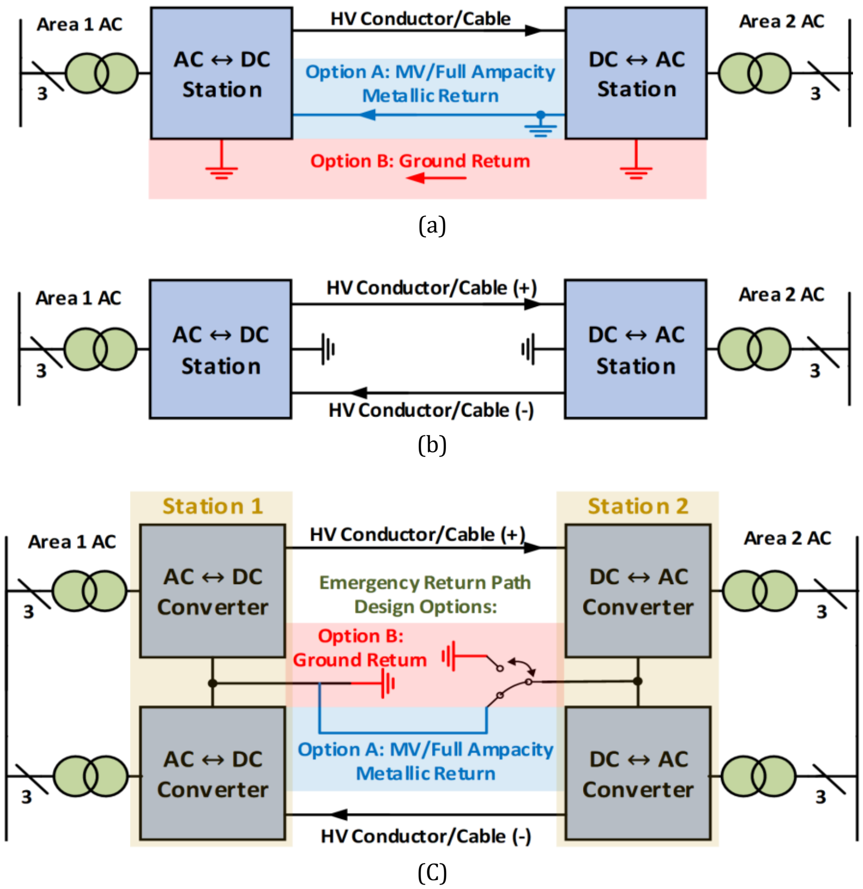


Figure 12: Common HVDC transmission configurations: (a) Monopole with both metallic and earth electrode return options. (b) symmetrical monopole. (c) Bipole with both return options. (two return options are presented in (a) and (c) for illustration, actual implementations use only one).

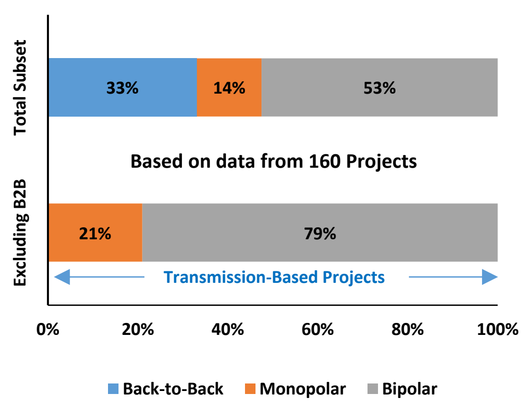


Figure 13: Market share of the main HVDC configurations, including and excluding Back-to-Back links, based on data from 160 projects [27].

3.2. Converter Transformers

Design requirements for HVDC converter transformers are different from that of AC power transformers. HVDC Converter transformers are needed to match the AC grid voltage to the converter AC voltage which is largely linked to the rated DC link voltage. Transformers also isolate the converters from the connected AC networks. They contribute to reducing the short-circuit current as their coils limit the fault-current rate of change. The leakage reactance of converter transformers is generally higher than that of AC power transformers. A leakage reactance of 0.1 p.u. is attractive economically and limits the reactive power losses which affect the converter P-Q capability, but fault considerations necessitate a modest increase, ranging practically from 0.15 p.u. to 0.18 p.u. [61, 130, 131].

Compared to conventional transmission transformers, a converter transformer is designed to withstand DC and AC stresses; thus, increasing its insulation requirements and size. The DC stress is significantly more in LCC than the VSC case, although some conventional VSC design alternatives also exhibit high levels of DC stress [13].

Transformers in 12-pulse LCC converters are connected in Y-Y, Y-Δ configuration (Figure 9b) in order to mitigate the system generated low order harmonics, especially the 5^{th} and 7^{th} components, and suppress their propagation to the AC network [130].

Converter transformers in both VSC and LCC stations typically utilize automatic On-Load-Tap-Changers (OLTCs) to regulate grid and converter voltages within allowable tolerance limits [132, 133]. OLTCs are operated to maintain constant DC side voltages by correspondingly fixing the converter interfacing AC voltage to mitigate commutation failures [62, 134].

In terms of physical transformer connections and used types in HVDC transmission, then the main connection configurations for converter transformers are: i) single-phase, three-winding. ii) three-phase, three-winding. iii) single-phase, two-winding. iv) three-phase, two-winding. A major selection criterion for the transformer type is its rating as it directly affects the size and ease of transportation. Highly rated transformers for high power applications are physically enormous, making it impractical to transport them to site. Instead, option (iii) is more commonly used in HVDC applications as it is easier to transport, where transformers are connected in three-phase arrangements at the station, while maintaining adequate phase-balancing. This makes it easier to add spare transformers on site at a reasonable cost for increased system reliability [13, 135].

The practicality of this option is evident at Ultra-HVDC ratings, where up to 24 single-phase transformers are needed per station (two 12-pulse LCC converters are connected in series per pole to withstand the ratings, with each requiring six single-phase, two-winding units). Additional 4 transformers are typically added as spare parts in similar cases [61]. Figure 14 compares options (ii) and (iii) for a 6-pulse station for illustration, while presenting the scaled size of a UHVDC 800-kV transformer from ABB for context [13]. As discussed earlier, the current maximum available converter transformers unit rating is 1,100 kV from ABB & Siemens.

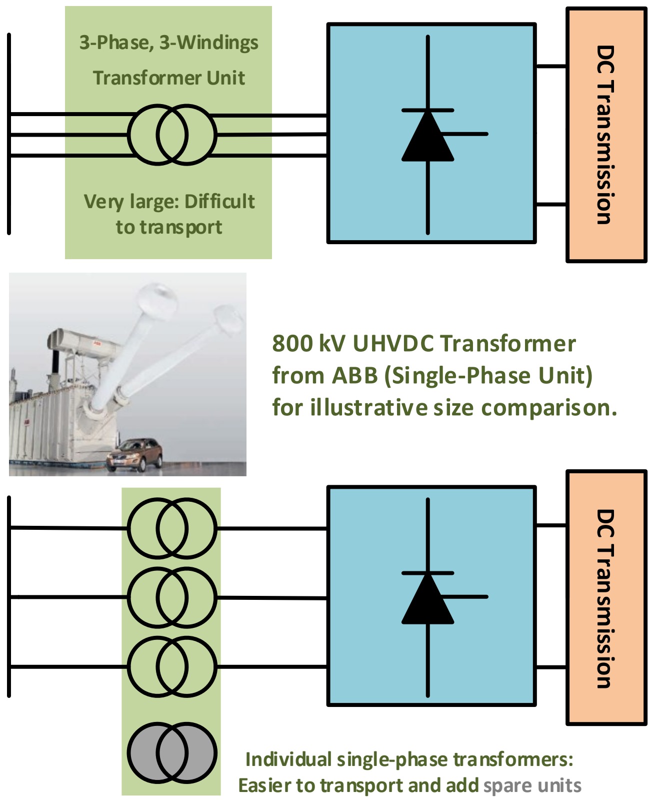


Figure 14: Comparison between common converter transformer installation options (single-phase vs. three-phase units).

3.3. Transmission Assets

HVDC transmission types are classified into overhead (OH) conductors and underground (UG)/subsea cables. The use of a specific type per project is dependent on the HVDC link terrain, and influenced by adopted policies and regulations.

3.3.1. HVDC Conductors/Cables Overview

Overhead HVDC transmission is well-established at very high ratings for long distances with several commissioned and operational ±800 kV links, especially in China and India. The first ±800 kV/6,400 MW link was built in 2010, linking the Chinese Xiangjiaba-Shanghai regions at a distance exceeding 1,900 km.

On the other hand, cable-based HVDC links are mainly used for offshore markets interconnection and wind-farms grid integration. Cable based transmission is typically adopted at considerably shorter distances compared to OH conductors in HVDC projects as the breakeven distance described by Figure 1(a) is much shorter for DC cables due to the excessive required reactive compensation with AC cables [136]. Having said that, the maximum ratings achievable by cable-based HVDC links so far are currently limited to 2,200 MW/600 kV (Western HVDC Link) between Scotland and North Wales, utilizing LCC technology with Mass-Impregnated (MI) cables [137-139]. The longest cable-based project to date is NorNed at 580 km. This record is set to be broken by the upcoming Nord Link (623 km in 2020), Viking Link (770 km in 2020) and NSN Link (730 km in 2021) projects, all linking Northern European countries through submarine cables [140, 141].

Although converter technology and ratings are essentially the same for both OH and cable transmission options, there is a clear gap between the maximum available ratings for the two options as illustrated by Figure 15 [142]. It should be noted that the use of UG cables is sometimes adopted over cheaper OH alternatives to comply with local regulations or public concern about the visual impact of OH lines especially when increasing the link power capability is not an essential design parameter. One example is the SydVästlänken (South-West) link between Norway and Sweden, rated at 1,200 MW and consisting mainly of UG cable sections to minimize its environmental impact on the surrounding areas [143]. Cables are also not exposed to transient faults induced by lightning or ambient environment condition as compared to OH lines, thus providing more operational reliability [144].

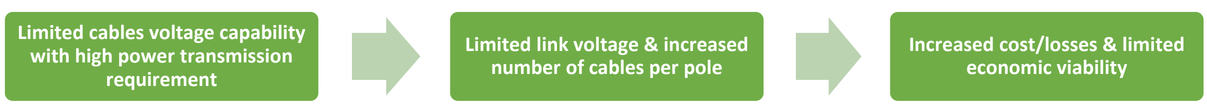
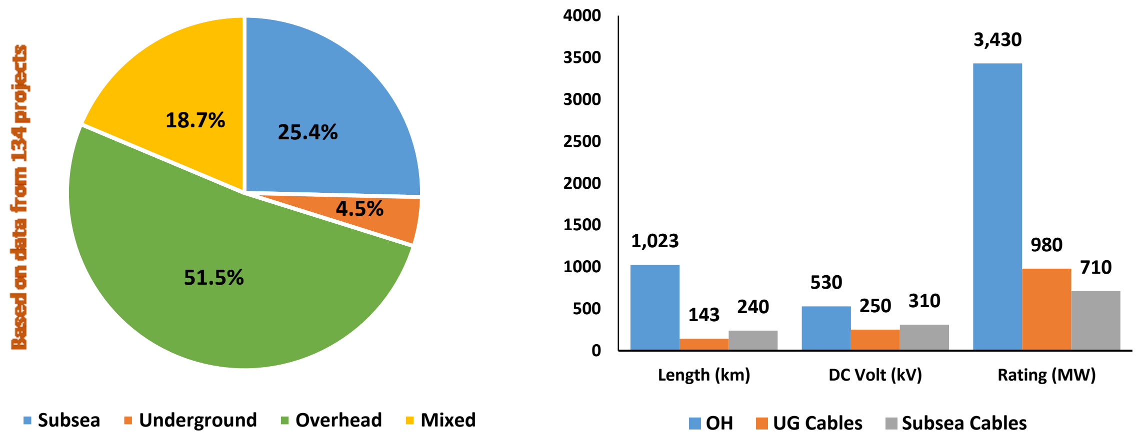


Figure 15: Qualitative summary of the limited power transfer capacity of DC cables.

Another subset of 134/252 projects with transmission distance breakdown from BNEF data is used to analyse the level of adoption of each transmission method. [27]. These projects are classified into OH, UG and Subsea. A project is classified in this work into one of these categories if it dominates the overall link distance by more than 70%. Otherwise, the transmission project is categorized as mixed. For instance, it is found that 96% of the covered projects in Asia (mainly China and India) are dominated by OH conductors, which is justified by the transmission terrain and the required long transmission distance.

Figure 16(a) summarizes the global classification of the considered subset of projects based on transmission type, where mixed projects worldwide typically consist of more UG component compared to OH. Figure 16(b) also summarizes the average project length, voltage and power ratings for each HVDC transmission technology type based on the same data subset.

Two main types of HVDC cables are used in market: i) Mass-Impregnated (MI) and ii) Extruded Cables (XLPE). These two types are compared in the next subsection as they are suitable for different technologies with different development paces.



(a) (b)

Figure 16: HVDC market share of different transmission types: (a) technology adoption distribution. (b) Average ratings/length per type. Raw data source: [27].

3.3.2. HVDC Cables Comparison

Mass-Impregnated (MI) cables were used in HVDC transmission systems as far back as the 1st commercial HVDC project in Gotland, Sweden in 1954 at 100 kV [13]. Their insulation system is based on lapped paper tapes that are impregnated with a viscous, oily, compound [38, 145]. This cable technology is well-proven and operationally compatible with both VSC and LCC converters which means it continues to be used in many submarine HVDC projects up to the highest available rating in the Western HVDC link [137].

However, another competitive technology has been receiving a major research focus to provide more sustainable and flexible alternative to the existing MI cables technology. Extruded DC cables technology was first applied in HVDC transmission systems in 1999, notably, at the same location of its MI competitor in Gotland, Sweden at 80 kV rating [13, 146, 147]. The insulation material in extruded HVDC cables is based on cross-linked polyethylene (XLPE), hence they are typically referred to as XLPE cables [38]. Their main advantages compared to MI cables are: i) Low weight and design flexibility, leading to easier transport and site installation. ii) More mechanical robustness. iii) Faster manufacturing process. iv) Environmentally friendly with no oil leaks and use of recyclable materials [16]. A more comprehensive technical comparison between the different HVDC cables technologies is found in [38].

XLPE cables are used primarily in VSC-HVDC links, as they are prone to failure due to the excessive DC stress from the power flow reversal when used in LCC-HVDC links. Despite this, a few exceptions exist where cables are designed with high DC breakdown strength to accommodate voltage polarity reversal, as in the Japanese Hokkaido-Honshu HVDC link [146, 148]. The development in XLPE cables market share is thus dependent on the increasing VSC market share. Figure 17(a) summarizes the MI and XLPE DC Cables market development overtime based on EuropaCable data [149]. It is expected that XLPE cables will soon have a dominant share of the HVDC market. Figure 17(b) compares the cost of MI and XLPE cables at similar ratings (without installation cost), and indicates a reasonable gap (by 2015) that may be justified economically in some cases based on the easier XLPE cables installation [105].

Currently, the maximum implemented and operational rating of a project using XLPE cables is 2,000 MW/±320 kV at the INELFE link (2x1,000 MW parallel links) [27, 118, 150]. The NEMO Interconnector, commissioned in 2019, operates at ±400 kV in a symmetrical monopole configuration, utilizing XLPE submarine cables manufactured by JPS Japan [151]. Further advances are expected with next generation 525 kV XLPE cables already announced by ABB [39], and 640 kV cable prototypes recently tested and announced by NKT [147]. Other notable DC cable manufacturers with ongoing progress are Nexans, Prysmian, Furukawa and LS Cables. Table 4 summarizes the comparison points between MI and XLPE cables for HVDC applications.

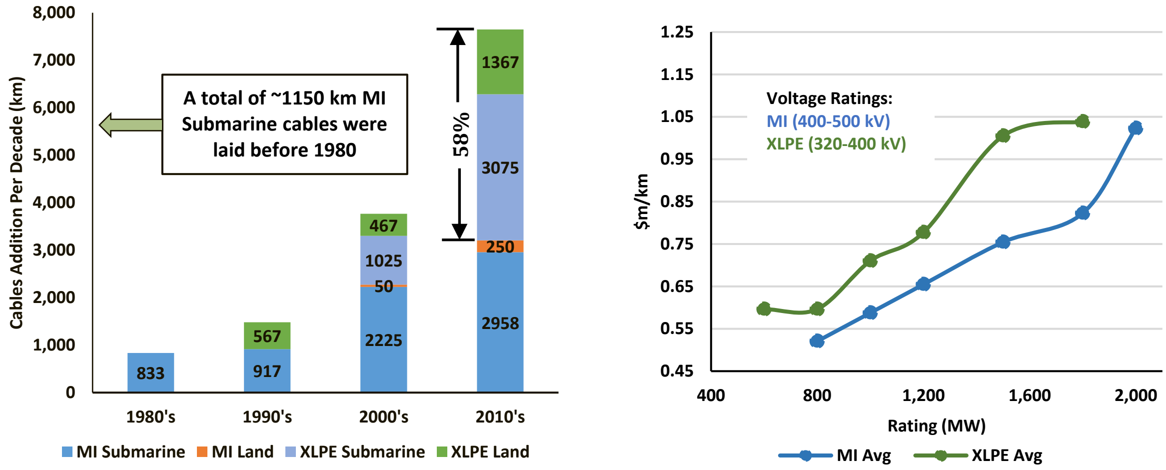
On the other hand, superconducting cables are theorized as a potential competitor in HVDC transmission as their technology provides significant advantages compared to existing options in terms of reduced size and losses. They also provide increased power transmission capacity that could match OH options in efficiency. However, the technology is still very expensive for long-distance implementation with limited availability and requires extensive additional research and validation [152, 153].

Table 4: Comparison between XLPE and MI DC cables technology.

Cable Type	Mass Impregnated (MI)	Extruded (XLPE)
Insulation Type	Paper insulated/Oil filled	Polymer (cross-lined polyethylene)
First Use for HVDC	1954	1999
HVDC Applications	LCC & VSC	Mainly VSC (limited suitability for LCC due to voltage reversal)*
Mechanical Weight/Installation	Higher/Harder	Lower/Easier
Maximum Rating (Project-Based)	2,200 MW/±600 kV (Western Link) [137]	2,000 MW/±320 kV** (INELFE) [118]
Longest Distance	580 km (NorNed) [127]	400 km (NordBalt) [147]

* Special types of XLPE cables are rarely used in LCC projects (e.g. the ±250 kV Hokkaido-Honshu link in Japan) [146, 148].

** NEMO Interconnector commissioned in 2019 uses 400 kV XLPE cables manufactured by JPS of Japan [151]. ABB has also recently manufactured 525 kV XLPE cables that should be soon in service [39].



(a) (b)

Figure 17: XLPE and MI cables comparison: (a) DC cables length up to 2020 [149]. (b) average costs comparison of ~400 kV cables at different ratings, excluding installation which is easier/cheaper for XLPE cables [105].

3.4. HVDC Controllers

The reliability and complexity of HVDC power flow control systems vary based on the technology used (LCC or VSC) and the connected AC network conditions (strong or weak), in addition to the DC network topology (point-to-point or multi-terminal). This section briefly summarizes the main adopted techniques in controlling HVDC stations, including special considerations for weak AC grids. A detailed control review is out of the scope of this work. Relevant detailed references are provided where needed in the following subsections.

3.4.1. Control of LCC-HVDC Transmission

Typical control structures in LCC-HVDC transmission assign different tasks for each station in point-to-point links. The specific control architecture varies depending on the operating conditions (e.g. AC networks strength). The thyristors firing angle is the only controller output that could be manipulated at both ends to control the DC power and voltage. A converter station that operates in rectifier mode (sending-end) typically regulates the DC link current or power, whereas the converter station that operates in inverter mode (receiving-end) tends to regulate the DC link voltage directly or indirectly by controlling the thyristors' extinction angle within a narrow range in an effort to minimize reactive power consumption and risk of CF [46, 56]. The described control configuration is recommended when LCCs are connected to weak AC grids. A combination of PI controllers and Phase-Locked-Loops (PLLs) are typically used to achieve the reference set-points of the controlled variables while the OLTC of converter transformers can also participate in the voltage control action [154, 155]. In contrast, the inverter DC current control mode is normally invoked during AC and DC short circuit faults [46]. That is, switching between different control operating modes should be permissible by the control architecture.

Operating LCC-HVDC in weak AC grids requires special measures to mitigate the risk of commutation failure. For example, FACTS devices such SVC and STATCOM have been employed in a number of links to improve system stability and facilitate the control operation. Examples include the Baltic Cable link between Germany and Sweden, the IFA Cross-Channel link between the UK and France, and the Western link project within the UK [46, 139]. Finally, more detailed insights of LCC-HVDC control structures can be accessed from [46, 57, 62, 64].

3.4.2. Control of VSC-HVDC Transmission

VSC-HVDC systems are superior in terms of providing independent control of active and reactive powers, and their suitability for integration into weak AC grids. Vector control is the most used and straightforward method to manipulate the two control variables, i.e., magnitude and phase angle of the fundamental voltage generated by a VSC at its AC terminals by controlling the IGBTs gating signals. This is done to achieve the desired system level set-points [46]. Unlike LCCs, power flow direction does not dictate the converter station control mode and terms rectifier and inverter do not have physical influence apart from convention in some parts of the literature. However, the control objectives of both stations must be consistent from the point of view of power balance. As an example, in a point-to-point VSC-HVDC link, one of the converter stations must define a strict DC voltage level to facilitate correct operation and the other converter station must define the basis in which the real power is to be dispatched. With both stations having additional control degrees of freedom that could be used to control reactive power or AC voltage. Besides vector control, there are other methods in literature to control VSC-HVDC systems [156, 157].

Unlike LCC-HVDC, the use of self-commutated switching devices that can switch several times per fundamental period enables techniques such as pulse width modulation (PWM) to be employed with VSC-HVDC system. This permits the system to be seen conceptually as a true current controlled voltage source, capable of injecting limited and controlled active and reactive currents during symmetrical and asymmetrical AC faults to support AC networks. However, ensuring stable operation of VSCs in weak AC grids requires advanced PLLs or alternative control implementations such as the power synchronization method, etc., [46, 158-160]. It is worth underscoring that for the MMC type VSC-HVDC links, more controllers for managing internal dynamics will be required, but such aspects are beyond the scope of this paper.

Philosophically, the control of VSC-based Multi-Terminal HVDC networks could be seen as simple extension of point-to-point HVDC link, and it is an evolving topic that continues to attract research attention. Master-slave, DC voltage margins and many types of linear and nonlinear droop controls are just a few examples of methods proposed for ensuring satisfactory operation of multi-terminal HVDC networks during normal and abnormal conditions [161-163].

3.5. HVDC Networks Protection

LCC and VSC based HVDC transmission require different protection systems that vary between point-to-point and multi-terminal HVDC links. For instance, the inherent LCC characteristic of unidirectional DC current with highly inductive DC link greatly restrains the rate-of-rise of DC fault current. In addition, the use of switching devices with bipolar voltage blocking capability is advantageous in terms of increasing the system immunity to DC fault current. Several fault-detection techniques for point-to-point LCC converters are presented in literature, discussing fault isolation algorithms and limiting potential thyristor commutation failures following a fault condition [164-166].

On the other hand, the bidirectional DC current of VSCs, and its adoption of switching devices with unidirectional voltage capability, in addition to increased DC fault level due to the large transient fault current from the energy intensive DC-Link capacitors discharge, exacerbate the vulnerability of VSC to DC faults [167]. That is, the DC side in VSC-HVDC is prone to abrupt and very high rates of fault current rise. This fact influences the transmission type selection as the majority of existing VSC projects either use Back-to-Back configuration or cables transmission since overhead lines are exposed to more short-term DC faults (e.g. due to lightning) [168]. The use of DC superconducting fault-current limiters (SFCL) within VSC-HVDC transmission is suggested in the literature to mitigate this issue [169-172]. HVDC protection is thus dependent on a combination of circuit breakers and converters fault blocking operation. The development status and main trends in HVDC protection are discussed here.

3.5.1. AC Circuit Breakers in HVDC Transmission

AC Circuit Breaker (ACCB) technology is well-developed and available at very-high ratings using gas-insulated switchgears to accommodate different needs, up to 1,100 kV - 1,200 kV [173]. The operation of ACCB depends on fault-current interruption at the natural cyclic zero-crossing point of the AC current (Figure 8), typical response time is 2-3 cycles (i.e. 40-60 ms in a 50-Hz network) [168, 174]. A tripping time of this magnitude is acceptable in most AC networks as the fault current rate of change is limited by the inherent inductance of the AC transmission lines, but poses serious challenges for multi-terminal HVDC networks.

AC breakers are widely used in point-to-point HVDC protection due to their low cost and reliability [175, 176]. Different control algorithm and fault-handling techniques are used to coordinate their operation with other protective equipment (e.g. in MMC implementation) [177]. Protective device coordination is used in VSC stations to limit the contribution of the AC network to DC fault level by opening AC breakers, since inverse-parallel diodes connected to IGBT modules conduct during fault [178]. In contrast, utilizing AC side breakers for blocking DC faults typically results in a complete shutdown of the fault-side converter station until normal connection conditions are restored. This leads to a temporary loss of the ancillary AC grid support services that could be provided by VSC-HVDC stations (i.e. voltage support) [178, 179].

3.5.2. DC Circuit Breakers

Failing to rapidly isolate a DC faulty line in MTDC networks can lead to a fast fault propagation through the healthy network assets, causing unnecessary tripping and outages. The rate of DC fault current increase in VSC-HVDC is particularly rapid due to the low DC network impedance and the lack of inherent current limiting reactance as in LCC-HVDC [180, 181]. DC breakers thus have an average tripping time requirement of 3-ms to 10-ms [44, 182]. This requirement is summarized by Figure 18a, whereas Figure 18b illustrates a DC grid fault scenario. The DCCBs connected to the faulty line should trip fast enough to prevent fault propagation.

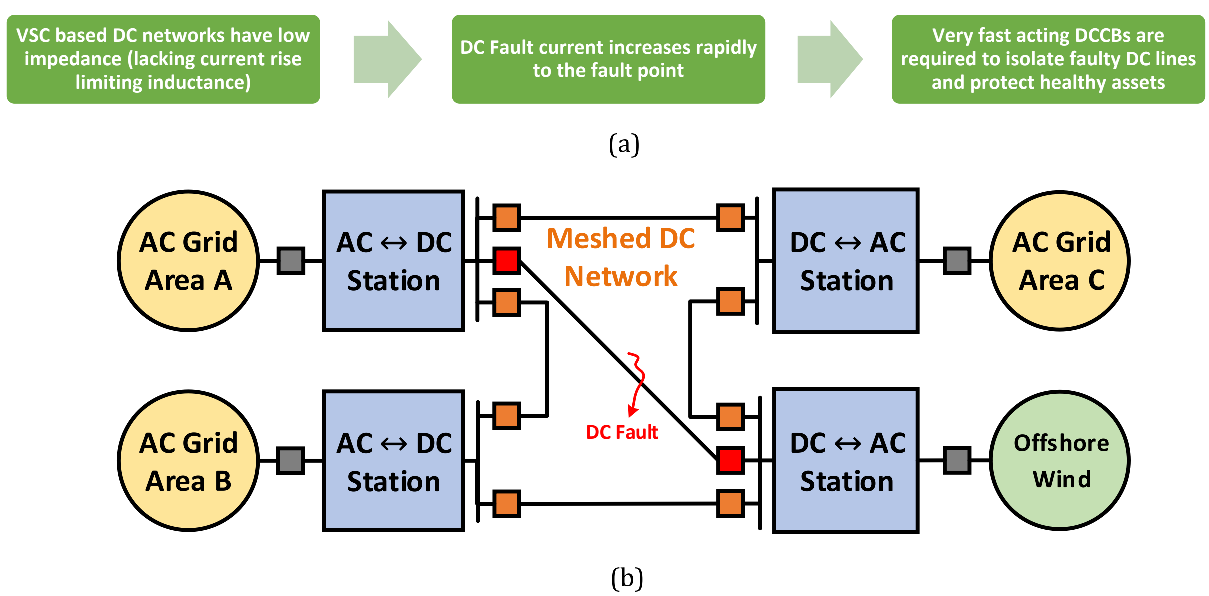


Figure 18: (a) Qualitative description of the rapid fault current increase rate in DC networks and the resulting fast DCCB tripping requirements. (b) Illustrative DC grid fault scenario

There are a limited number of operational, small-scale, VSC-MTDC networks already implemented as real-life case studies to test different protection scenarios. The main example is the Zhoushan DC grid in China, consisting of 5 interconnected VSC stations at ±200 kV [44]. Different protection scenarios including the use of DCCB technology for this DC grid are discussed in [97, 183]. Several manufacturers are actively testing DCCB prototypes and recent sources indicate successful implementation of 200 kV hybrid DC breakers [44, 184], with potential technology development up to 500 kV. The fault blocking capability of new converter station technologies (i.e. MMC based VSC) can also play significant, cost-effective role in DC networks protection in coordination with DCCB devices [78, 93]. The development of reliable high voltage DC circuit breakers (DCCB) has been the subject of extensive R&D activities to overcome existing protection limitations. That is, one of the main prospects of MTDC network protection today suggests the use of non-fault blocking converters such as half-bridge MMC plus fast acting DCCB and selective protection strategies to isolate the faulted line.

The DCCB technology solutions used by ABB and Alstom are discussed and compared in [185], while highly-rated GEIRI breakers are introduced in [44]. The hybrid technology used by different manufacturers is based on a combination of solid-state semiconductor electronic devices (thyristors and IGBT) and fast mechanical switches/disconnections. The basic structure of hybrid DCCB systems is similar, consisting of: i) low-losses normal flow branch. ii) main circuit breaker branch (MCB). iii) Absorption branch utilizing surge-arrestors. DC breaker designs should consider bi-directional fault-current blocking capability in VSC systems to accommodate current reversal when changing power-flow direction [186]. Figure 19 summarizes the operational sequence of ABBs [187] hybrid DCCB design [187].

Different hybrid DCCB design variations have also been proposed in literature (e.g. replacing the current-limiting inductor with a superconducting fault current limiter (SFCL) [184]). Further, less-commonly adopted, DCCB operation techniques are discussed in [186].

Due to the breaker control complexity and the large number of required semiconductor switches, the DCCB cost is significantly higher than ACCBs [179]. Further research and development efforts are required to increase the available DCCB ratings at a reasonable cost to ignite the reliable adoption of MTDC networks. Finally, the current status and requirements for DCCB development are summarized by Table 5.

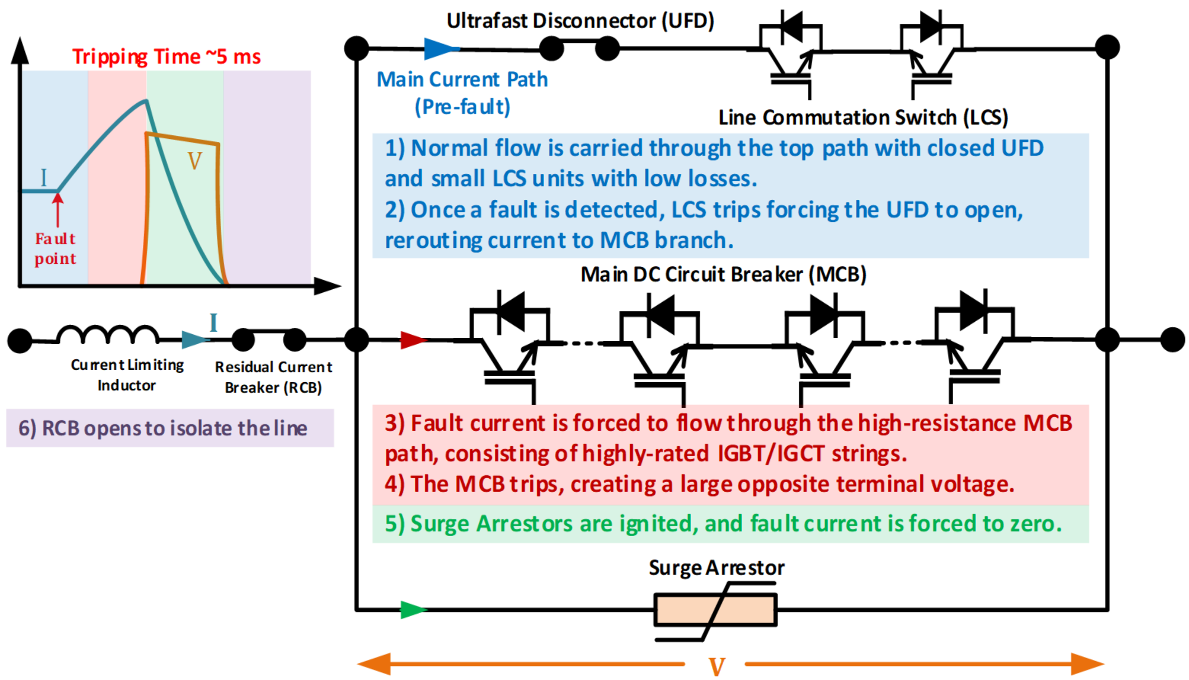


Figure 19: Operating principle of ABB DC Circuit Breaker.

Table 5: DCCB progress summary and development status.

Parameter	Status			
Main Application	Multi-Terminal VSC Based DC Networks (MTDC)			
Common Technology	Hybrid Breakers (Mechanical Disconnectors & Solid State Devices)			
Available Prototype Ratings [44]*	Supplier	ABB	Alstom	GEIRI
	Voltage (kV)	80	130	200
	Trip Time (ms)	5	5.5	3

* The given data is based on publically available documentation and announcements. Newer prototypes with higher ratings up to 200-500 kV may also be under development by lead technology manufacturers.

3.6. HVDC Technologies – Case Studies

Understanding the capabilities and key differences between transmission technology alternatives is essential for system designers to make proper selections while efficiently meeting the transmission capacity and system criteria. The following case studies for two transmission projects discuss the technologies used and the rationale behind their selection, in light of the previously presented comparisons between HVDC and HVAC and between the HVDC technology alternatives, to provide the reader with practical context from real-life projects.

3.6.1. Case Study 1: INELFE France-Spain HVDC Interconnector (VSC)

Interconexión Eléctrica Francia-España (INELFE) is an HVDC interconnector that was commissioned in 2015 between France and Spain [38, 39, 188]. This France-Spain link is rated at 2,000 MW/±320 kV (consisting of two parallel 1,000 MW lines) and extends over 64.5 km between Baixas town in France and Santa Llogaia in Spain.

HVAC vs. HVDC: At a distance of 64.5 km, overhead AC transmission would have been a more economic option. However, the increasing social opposition for constructing overhead transmission lines in Europe and the consequent debates limited the transmission options for INELFE to underground cables. HVDC thus became the more reasonable techno-economic solution as 64.5 km falls within the HVAC vs. HVDC breakeven distance range [118].

Converter Stations (LCC vs. VSC): A preliminary study was conducted to determine the most suitable technology for the link. Automatic control of reactive power exchange was a design requirement as some power contingency incidents were recorded near the border area. Thus, the new link was required to be capable of supplying up to 30% of its MW rating as reactive power to the connected areas [118, 189]. Moreover, the connected AC grids had a low short-circuit ratio, which made it more challenging to select LCC. As a result, VSC technology was adopted due to its independent real/reactive power flow, grid support capabilities and fast power-flow reversal by changing current direction, which is preferable in bidirectional, cross-border, energy trading links [189].

VSC Technology Selection: From the available VSC options, Half-Bridge based MMC technology was selected due to its positive effect on dynamic performance and AC harmonics elimination. The number of modular levels was set to 401 [190, 191]. This way, Siemens was able to effectively generate pure sinusoidal voltages at the converters AC interfacing points, effectively eliminating harmonics. The selected connection configuration was symmetrical monopole, in order to use DC cables at half the pole-to-pole voltage and maximize the transmitted power. Two parallel symmetrical monopoles were constructed (2x1000 MW) to accommodate the design power flow requirement with moderate available VSC power/voltage ratings, and to increase redundancy (i.e. in case one link is temporarily lost, the other would operate normally at 1,000 MW/±320 kV, in a similar fashion to bipolar configurations) [118].

Transmission Cables: The use of XLPE cables from Prysmian was possible due to the adoption of VSC technology for the project. At the project awarding time in 2010, the maximum available XLPE cables rating was ±320 kV. The use of such cables in INELFE was the first in any HVDC project, with a power rating of 500 MW for each HV cable [39, 188].

Collectively, it can be observed from this case study how the technology selection and the number of converters/cables can sometimes be adapted to the available technology limits while maintaining the high-level requirements in terms of power transfer and grid support. Finally, the budget for constructing the INELFE France-Spain link was estimated at 700 million euros [188].

3.6.2. Case Study 2: Western HVDC Link in UK (LCC)

The Western HVDC link was constructed to expand the transmission capacity between Scotland and England/Wales. The link was required to achieve a rating of 2,200 MW at a total estimated budget of 1 billion Pounds Sterling. The link voltage rating was set to ±600 kV, spanning over ~420 km, including 385 km submarine cable sections [139, 192]. The project was initially planned to be commissioned by 2015. Consequent delays led to a partial inauguration of 900 MW transmission capacity in 2017, with the full capacity planned to come into operation by the end of 2018 [192, 193].

HVAC vs. HVDC: Both transmission options were initially considered for the planned Western link. However, overhead and onshore cable options were discarded based on potential land disruption, high visual impacts and the excessive planning/consents time. Clearly, an offshore connection of ~400 km is well beyond the HVAC vs. HVDC breakeven distance and thus HVDC was selected [139].

Converter Stations (LCC vs. VSC): Although VSC technology provides far more technical advantages when compared to LCC as described throughout this work, the initial project proposals between 2009 and 2012 concluded that LCC is more suitable for the Western link. The fairly strong networks with high SCRs at both sending and receiving ends contributed to this decision, in contrast to the INELFE interconnector case [139]. Furthermore, the planned high-voltage transmission at ±600 kV was more suitable with LCC stations given their track record at higher voltages, although additional reactive-power support equipment (e.g. SVC) and large, switched, harmonic filters were required. A preliminary cost-based comparison between VSC and LCC for the project is presented in [193], attributing more cost uncertainty to VSC although it was within a comparable range to that reported for LCC. However, the financing report concluded that LCC was the only technology at the time to be commercially available for the requested capacity. Rigid Bipolar configuration with 12-pulse converters was adopted for the link, with no emergency current return path to avoid additional long conductor cost, and to comply with environmental requirements in case of the earth electrode return path option [129, 154].

Transmission Cables: Given the adoption of LCC, Mass Impregnated cables were used to connect both stations due to their availability at higher ratings up to 600 kV, unlike XLPE technology that was commercially limited to 320 kV at the time. Furthermore, the risk of excessive DC stress and breakage of XLPE cables with LCC under voltage polarity and power-flow reversal conditions rendered the option incompatible as this link required bi-direction flow capability.

3.6.3. Case Studies Comparison

Comparing both studied links, one can notice the similarity in their power ratings (2 GW and 2.2 GW), in addition to the similar projects announcement timeframe (early 2010s). However, each was implemented using different station and cable technologies. While the available XLPE cables rating was limited to ±320 kV at the beginning of this decade, INELFE utilized symmetrical monopoles with double VSC stations to accommodate required 2 GW power transfer through the link using VSC/XLPE combination.

One can argue that a similar technique could have been used at the Western UK link with VSC stations and XLPE cables, which would have facilitated a more convenient integration of the link assets to any planned Multi-Terminal DC network in future. [193]Though, it was eventually deemed more appropriate by network planners to resort to the well-developed LCC technology, considering the strong network conditions at both transmission ends. Although future nuclear shutdowns at the Scottish end may negatively affect the network strength, leading to further investment in synchronous compensators. The presented analysis demonstrate the role that the risk factor plays in technology selection, especially for projects rated at the VSC-LCC technology boundary limits. Which require deeper feasibility investigation to evaluate the available options on technical, economic and operational basis.

Finally, in terms of reliability, both projects have been operational for only a short time and thus benchmarking their failure history is improper. Having said that, both links mainly utilize underground/subsea cables for transmission, and it is noted by analysing data from CIGRE reliability reports [194, 195] that cable-based projects have an average forced annual unavailability time due to outages and failures of around 3.52%. Though, the adoption of rigid bipolar configuration in Western HVDC link is likely to decrease its reliability further when compared to the double symmetrical monopoles in INELFE project because the power transfer of a rigid bipolar link is totally lost in case of a permanent single cable fault.

4. HVDC Transmission Challenges

This section briefly summarizes the main challenges for the HVDC system components discussed earlier, and then discusses more comprehensively some system-level implementation and operational challenges. A relevant case study to these challenges is then presented.

4.1. Component Level Challenges

The previous section introduced a comprehensive component-level assessment for the state-of-the-art of different HVDC system components, including some of their limitations. For instance, technical boundaries of LCC converters when compared to VSC are evident in terms of their excessive reactive power consumption requirement, in addition to their lack of inherent grid support capability, which is especially important in weak AC grids. Hybrid HVDC systems and the use of peripheral devices, mostly controlled by VSC based power electronics, is introduced in literature and implemented by various projects to overcome such limitations. LCC stations are also ill-suited to MTDC networks mainly due to the requirement of reversing their DC terminal voltage for each power-flow reversal.

In contrast, the main presented challenges for VSC are relevant to the technology development pace in terms of the current moderately available ratings and higher costs of VSC stations when compared to LCC. In addition to the lack of high-voltage DCCBs, which technically limits the implementation of VSC based MTDC grids.

The main challenges related to transmission assets can be classified as technical and legislative. Cable ratings are commercially limited to 600 kV in today's market. While overhead transmission, although cheaper and available at higher ratings, is more prone to short-term faults and is facing increasing opposition from the public in densely populated areas due to its visual and environmental impacts.

4.2. System Level Challenges

High-level system challenges are mainly related to the operation of HVDC networks from regulatory and economic points of view, in addition to addressing the feasibility question of investing in such high-voltage transmission projects compared to other alternatives.

4.2.1. DC Networks Technical Standardization

This point is becoming increasingly important as reliable MTDC implementation has not only become a question of technology readiness, rather, a regulatory one as well. For instance, the anticipated high demand on MTDC networks makes it important to develop compatible DC grid codes and standards, because point-to-point links with different voltage levels (e.g. ±150 kV and ±320 kV) are already implemented and could be interconnected as part of future planning. Thus requiring the use of DC-DC transformers to integrate such systems operating at different voltage levels into a single interconnected DC grid. Some ideas and converter designs with interesting fault-blocking capabilities are already emerging in literature [78, 196]. More importantly, International institutes such as IEEE and CIGRE are establishing the process of developing the required standards [197, 198]. Although these are non-binding standards, they serve as an incentive to Transmission System Operators (TSOs) and regulatory bodies to take similar steps. Common standards also facilitate the interoperability of multi-vendor converters (i.e. compatibility between different converter topologies supplied by different manufacturers, which is critically important to maintain market competition). Finally, different aspects of HVDC grid code requirements, implementation suggestions and a summary of relevant social/political challenges are presented in [15].

4.2.2. DC Networks (SuperGrid) Operation

The "SuperGrid" concept aims to interconnect different AC electricity networks. Such schemes increase the security of supply of the individual interconnected networks and facilitate the interfacing of large-scale renewable energy sources directly to the DC networks [199].

However, the emergence of DC grids requires extensive planning and coordination between different network operators, especially when they are operated across different countries. That is, questions of cost-benefit optimization and network ownership would arise in such a scenario, in addition to the willingness of neighbouring markets to participate in setting new energy policies and to change their investment plans. For instance, it is estimated that investments of up to 600 billion euros may be required for an interregional European grid infrastructure. Whereas large French investments in nuclear power are recently reported, boosting its share of the local energy mix to ~75%. As a result, heavy investments in alternative energy pathways in the short term from all concerned bodies or governments is questionable [15].

Having said that, it is important to address that the process of constructing a cross-border DC grid is incremental. That is, small-scale multi-terminal HVDC networks can be constructed by a single TSO or small-clusters of TSOs. Examples of that are the North-East Agra network in India (Although currently operated using LCC technology) [199, 200] and the North Sea offshore interconnection in Europe [15]. The development into larger DC grids can eventually be performed through expanding the existing point-to-point or multi-terminal networks in a gradual manner. In this case, the participation of a large group of TSOs requires setting clear rules for network operation and ownership to govern the energy flow between different parties [199, 201].

4.2.2.1. High-Level DC Grid Control Topologies

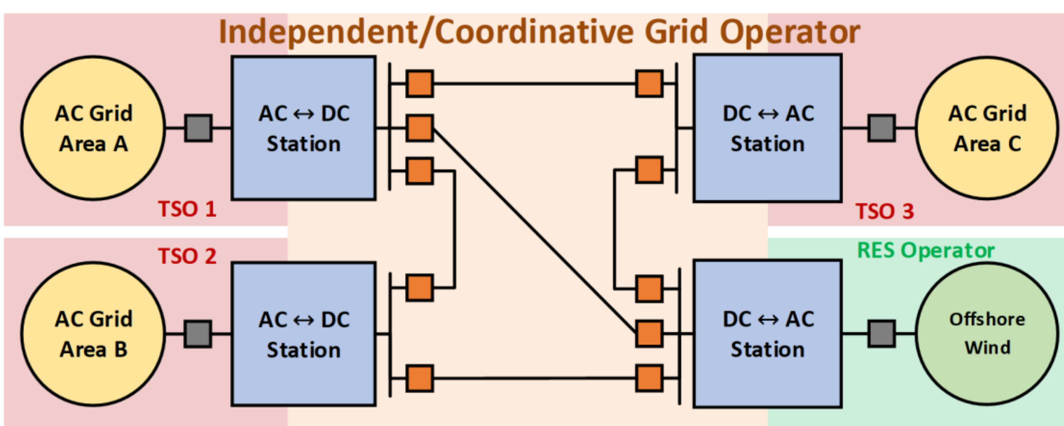
Several coordination methods between involved TSOs are presented in literature. Most Notably, coordinative, independent and integrated grid control [199, 201, 202].

Coordinative DC Grid Control: In this scheme, the DC network is operated by an entity whose policies and practices are set by the participating TSOs. This entity is in charge of the DC grid assets including the converter stations. It handles the power flow through the MTDC system and ensures a smooth set-point transition following unscheduled power-flow changes/ interruptions in a way that must benefit all participating TSOs. In contrast, this entity applies incentives/penalties to the participating TSOs following their pre-set rules and agreements. The European Network of Transmission System Operators (ENTSO-E) organization can be thought of as such an entity [176].

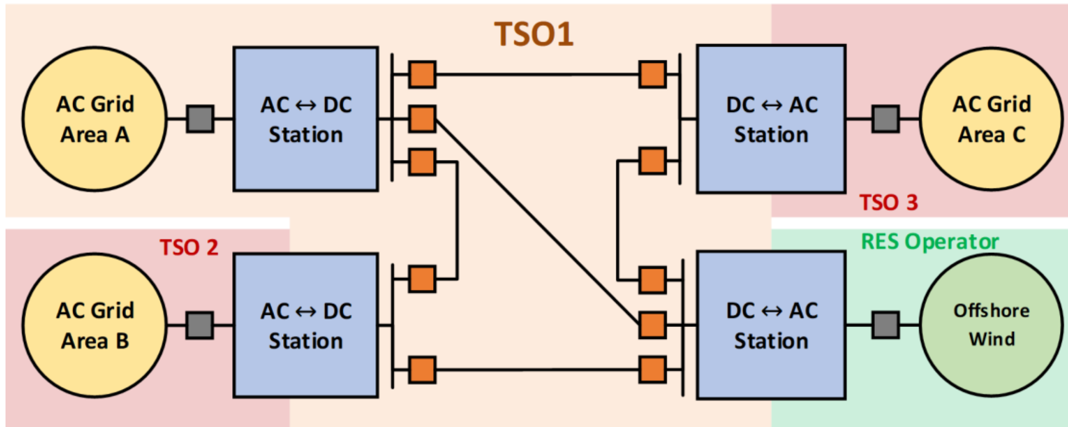
Independent DC Grid Control: In this case, the grid is controlled by an independent entity whose primary goal is to maximize its operational benefits while respecting connection rules and policies of each participating TSO. For instance, the independent entity is rewarded in this operative scenario for providing energy reserve to imbalanced areas, whereas part of this reward is paid back to the providing area. Having said that, designing the specific regulations to control DC grids under this scheme is challenging as it should balance the independent operator authorities and participating TSOs benefits.

Integrated DC Grid Control: One of the participating TSOs expands its operation in this case to add the DC network and converter stations at other areas under its operation. This TSO, as a network operator, could create bilateral agreements with the other TSOs to purchase services from one TSO and sell them to another, while taking responsibility of the network assets maintenance.

The control alternatives discussed above are summarized in Figure 20. Where implementing any of them, or possibly a combination, is dependent on the regional agreements, conditions, and investing parties in the particular inter-regional DC grid of interest. Other coordination and control techniques are also presented in literature, e.g. proposing distributed, shared control whereby all connected TSOs participate in sharing primary reserve in case of power imbalance to achieve an equilibrium operating point with unified frequency deviation [203]. Optimization techniques for optimal power dispatch in MTDC networks are also discussed in [204] to control energy flow within desired TSO set-points.



(a)



(b)

Figure 20: Different operating schemes of DC Supergrids: (a) Independent/Coordinated; (b) integrated

4.2.3. Utilization of High-Voltage Transmission Lines

Contemporary electricity networks integrate large-scale intermittent sources, which could sometimes lead to congestion problems in transmission line utilization. The generated renewable energy from wind, solar or hydro power sources is thus likely to be partially curtailed when one of the following conditions is met: i) lack of local demand or storage at the RES generation area, or lack of transmission infrastructure to distant load demand; ii) existence of transmission pathways that are congested by other competing sources either at the generation or load areas. The effects of high RES penetration on network congestion in Europe and China with case studies related to transmission grid expansion are discussed in [205-208].

Transmission grid infrastructure and expansion is a proposed solution in many such cases. By means of building new HVDC or HVAC transmission pathways to reduce network congestion and curtailed energy. However, investment decisions in new expensive transmission lines is risky and should be evaluated thoroughly in terms of the involved costs, technical and operational considerations [176]. Cost databases, economic HVDC models and HVAC vs. HVDC investment benchmarks are presented in literature to assist decision-makers in sizing and selecting the appropriate transmission technology for the intended application [107, 209].

In contrast to congestion, another important point to consider when constructing new High-Voltage lines for large-scale RES transmission is the local generation/demand trends and regulations in the receiving areas. Namely, building new transmission pathways should typically alleviate congestion and consequently curtailment. Yet, decreasing the energy import demand at receiving areas by switching to local generation alternatives due to lack of proper coordination can similarly cause renewables curtailment. A detailed case study discussing similar issues from China is presented in the next subsection. It serves to clarify the importance of proper HVDC transmission planning between the different involved parties to avoid transmission lines under-utilization.

4.2.4. Case Study: Interconnectors Utilization Challenge in China

China has a unique electricity market generation/demand distribution, with vast distances separating its RES rich areas (concentrated in northern and western regions) and main populated demand centres (in eastern and southern provinces). Large-scale RES plants are predominantly hydro, wind or solar, yet the lack of matching local demand in these generation areas or high-capacity transmission infrastructure to major population centres caused significant generation curtailment of RES resources in early 2010s. For instance, 17% of wind energy generation (~21 TWh) was lost in 2012 [208].

In parallel, the fast demand growth in densely populated areas facilitated the construction of several high-voltage transmission lines to utilize the excess available RES generation (see Figure 4 for the Chinese HVDC capacity expansion after 2010). As a result, RES energy curtailment was significantly reduced down to 8% for wind by 2014. This percentage was still high compared to the international average of wind energy curtailment, between 1% and 3% [208, 210]. Yet, the contribution of HV interconnectors in mitigating the curtailment issue in China was evident in this period, which is classified by [208] as the "1st curtailment wave".

This demand growth in Chinese electricity market later decreased, reaching 0.96% by 2016 [211]. On the other hand, the approval of constructing coal power plants was decentralized in 2014, allowing local province governments to commission new plants although the central government trend is to reduce the coal energy dependence in the country [211]. As of 2017, nearly 70% of China's electricity is generated from coal plants [212]. These factors, combined with the economic favourability of using decentralized coal plants by local governments rather than importing RES from distant provinces, led to the following consequences:

1) Establishing a trend of coal-energy overcapacity in several provinces.
2) Reducing the reliance on imported energy from distant large-scale renewable sources.
3) Establishing a 2nd wave of increased RES generation curtailment. However, this time due to the low demand in the receiving areas rather than the absence of transmission infrastructure.
4) Underutilization of UHV transmission links. Bloomberg estimated that average UHVDC lines utilization in 2018 is ~56% compared to even lower utilization of UHVAC lines [213].

As a result, the RES generation curtailment climbed to 110 TWh by 2016 [214], with 49.7 TWh from wind (rising back to 17%). Moreover, the overall lost wind energy from 2011 to 2016 approached 150 TWh. The equivalent CO_2 emissions to generating this lost energy from coal based plants is 0.12

billion tons [212]. More detailed analysis of the main factors affecting renewables curtailment are summarized and analysed in [208], specifically for wind energy.

Several recommendations have been recently presented in literature to mitigate this problem [208, 215-218], where Figure 21 summarizes the Chinese RES curtailment issue and the main recommended policies for its mitigation.

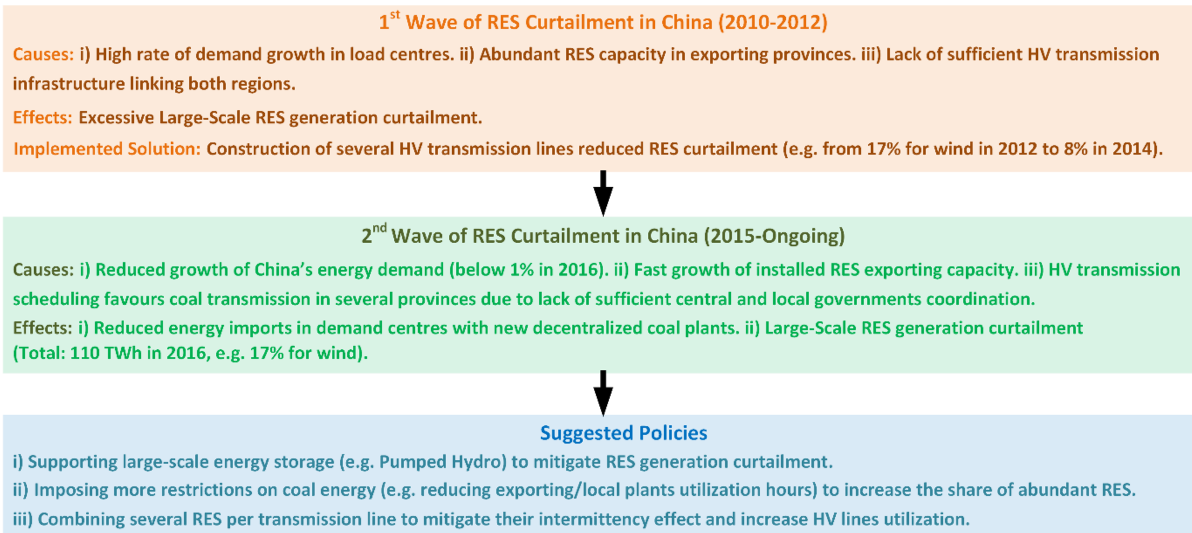


Figure 21: Summary of RES curtailment problem in China and its effect on HV Interconnectors Utilization

5. HVDC Technology/Market Horizon

This section discusses the potential growth of HVDC interconnectors in light of the expected technology development outlook, while analysing key influencing factors (e.g. demand variation and HVDC role in achieving national RES targets).

5.1. Market Development Landscape

The generated revenue from global HVDC links has been consistently increasing. Navigant research institute released a detailed HVDC report predicting its short-term landscape between 2013 and 2020, with average annual global HVDC interconnectors revenue exceeding 7 billion USD with a combined annual growth rate (CAGR) of 5.5% [219]. This profitable trend is expected to continue globally in light of the anticipated technology and regulatory developments.

5.1.1. HVDC System Components Outlook

Looking further into the future, the electricity infrastructure market is conservative in nature, meaning that even though technology prototypes may be readily developed, associated high costs and extensive testing requirements can cause significant delays in widespread implementation [75]. In contrast, demanding market needs and the strive to achieve national/regional interconnection and renewable targets could accelerate the development rate of new HVDC transmission technologies, mainly: XLPE cables with higher voltage and power rating, and hybrid DC switchgears for Multi-Terminal HVDC networks. In addition to accelerating the adoption of common regulatory standards.

In addition, the present generation of fault-blocking MMC-VSCs improve system resiliency to DC faults and speed up post-fault recovery, but is unable to prevent a drop of the power transfer between the connected AC grids to zero. Having said that, fault-blocking converters are still anticipated to play a significant role in multi-zones DC grids that would rely on relatively low cost partially selective protection strategies. Fault-blocking MMCs are thus undergoing extensive research and development activities to be successfully implemented in MTDC networks.

On the other hand, the UK Electricity Ten Year Statement predicts the utilization of 650 kV XLPE cables for 2,600 MW VSC transmission by 2030, compared to 750 kV at 3,000 MW for MI cables per DC bipole [105], accompanied by an increase in the maximum submarine laying depth from 1,600 m to 2,500 m over the same time interval [117]. This would pave the way for longer distance subsea transmission. The Advisory Committee on Electrical Transmission and Distribution (ACTAD) presented a more optimistic outlook for XLPE cables with 800 kV/2000 A predicted availability by 2030. The same source predicts an increase to the LCC-OH transmission limit from ±1,100 kV to ±1,200 kV [220].

The use of UG land cables for HVDC transmission is expected to grow, especially in Europe. Influenced by increased public awareness to environmental and visual effects of OH transmission, delaying the permitting process [106]. A practical case was recently observed in Germany, where public pressure led to rerouting of the planned Suedlink energy highway to use UG XLPE cables instead of OH transmission lines to mitigate their visual impact and environmental effects [221, 222].

Finally, Table 6 presents a summary of the forecasted component-level development horizon for HVDC transmission.

Table 6: Summary of the medium term horizon for main HVDC transmission system components.

System Component		Medium-Term Technology Outlook	Likely Impact
HVDC Converters	LCC	Maintaining its position as the main OH UHVDC power transfer technology	Pushing the maximum power transmission limit in Asia beyond 12,000 MW at ±1,200 kV [220]
	VSC	Available at higher ratings beyond 650 kV at lower normalized costs and station losses [105]	Playing vital role in MTDC development, increasing interconnected markets share and RES utilization (expected 65% of new HVDC projects by 2020 [75])
HVDC Cables	MI	Higher rating availability (750 kV at 3,000 MW per bipole by 2030 [105])	Pushing the maximum rating limits for projects with UG/submarine cable sections, yet with overall diminishing market share compared to XLPE
	XLPE	Higher rating availability (650 kV at 2,600 MW per bipole by 2030 [105])	Expanding its market share dominance , parallel to VSC technology progress and fuelled by the need to construct new MTDC links connected to offshore wind farms
DC Grid Protection	DCCB	Moving from MV prototyping stage to HV implementation around 2030 [220]	Accelerating DC grids implementation. Leading to increased MTDC networks share, increased security of supply and enhanced RES utilization
	VSC Based MMC	Enhanced control algorithms for DC fault-blocking at higher ratings [87]	

5.1.2. RES Interconnection Horizon

Interesting techno-economic studies are emerging in parallel to assess the feasibility of different interconnection scenarios. A recent work investigated a potential 3,300 km link by 2030 between Europe (UK) and North America (Canada) with a carrying capacity of 4,000 MW at ±640 kV. The authors concluded that the cost of such ambitious investment could be justified by the associated social benefits and the project high energy exchange potential [223].

The feasibility of MTDC networks implementation in Africa to support remote renewable energy utilization and interconnection of markets by 2030 was recently discussed in [224] with an estimated 18 Billion USD of required investments for grid renovation. Authors presented MTDC networks as an economically viable alternative to AC grid expansion. The generic role of HVDC transmission systems as a key enabler of large-scale renewable utilization is further discussed in [225]. Linking North Africa to Europe through MTDC networks to share the benefit of renewable energy sources (solar & wind) and increase security of supply is also discussed in [226] with 2030 and 2050 milestones. Interconnecting both regions is additionally discussed in various recent research articles, highlighting the vast energy utilization prospects that could be realized through an operational DC grid [223, 227]. Relevant to this, the authors of [228] present a potential roadmap for such African-European interconnection using HVDC to transmit dispatchable Concentrated Solar Power (CSP) power to Europe through Italy and Spain on the medium-term as the main connection points from

Africa to support a future supergrid implementation. Ultimately, helping both the EU and African countries to achieve their RES penetration targets. The following reference provides an overview on RES targets and implementation landscape in Africa [229].

Middle-East region is also viewed as a significant energy interconnection market, especially within the Gulf Corporation Council (GCC) area that has a current generation capacity of 148 GW, with a potential additional capacity from renewables exceeding 800 GW that can be used for energy trading with remote neighbouring areas as part of the Global Energy Interconnection (GEI) vision. Detailed discussion of interconnection opportunities in this region is presented in [43]. Further analysis of point-to-point and meshed HVDC pathways between the Middle-East-North-Africa (MENA) region and Europe to export CSP is presented in [230].

Another interesting recent study investigates the possibility of achieving 100% renewable energy penetration in Europe by 2050, and concludes that such a scenario would require increasing the wind generation capacity by 90% to 1.9 TW, maintaining an annual deployment level of 7.5 GW per year compared to an annual installation requirement of 10.5 GW of solar PV. Transmission infrastructure reinforcement would consequently be required to increase the utilization of such huge renewable energy capacity for both wind and solar to reach distant demand areas through HVDC transmission [231]. Similar analysis is performed for Australia in [232] with HVDC playing an active role to achieve such ambitious targets.

Collectively, Table 7 summarizes several renewable grid penetration targets from major international markets. HVDC links are essential to achieve these targets due to their vital role in long-distance transmission from remote large-scale renewable sources to load centres.

Table 7: Renewable energy targets in main global markets.

Market		Renewable Energy Target (E/P)*	Target Year
Europe		32% (E) [233] 15% (EU member states capacity interconnection) [7]	2030
China		770 GW (P) [234, 235] (37%-39% of total capacity in 2020 [1, 235])	2020
India		227 GW (P) [236] (48% of total capacity in 2022 [1])	2022
Russia		4.5% (E) [237]	2024
Brazil		45% (E) [226, 238]	2030
GCC Countries		80 GW (P) [239]	2030
Africa**		50% (E) [229]	2030
USA***	**New York**	50% (E) [240]	2030
	California	50% (E) [240]	2030

* E/P is used to distinguish (E)nergy generation from (P)ower generation capacity targets.

** This number is based on achieving individual existing national RES penetration targets by 2030 [229].

*** No nationwide target is set, yet IRENA estimates a potential of reaching 27% (E) of RES generation by 2030 with appropriate investment in interconnection infrastructure, in addition to renewable incentives [241].

5.2. HVDC Growth Factors Analysis

The growth in HVDC transmission system adoption is driven by various factors that are analysed here. As presented, the development of reliable HV technology is expected to accelerate the transition towards DC grids adoption from a technology readiness point of view. However, it is important to note that adequate network operation standards also need to be developed for cross-border energy exchange in future meshed DC grids.

Long-term, long-distance transmission UHVDC demand coming mainly from Asia is another important adoption factor, while considering the currently slow pace for commissioning new UHVDC lines in China as discussed earlier due to ongoing under-utilization. The future growth rate is significantly influenced by the implementation of RES support policies.

Collectively, the increased adoption of energy interconnection on a global scale and the ongoing attempts to standardize technology are likely to drive a parallel normalized decline in technology costs via economies of scale. This, in turn, could increase HVDC interconnection further as it becomes more economically viable and profitable compared to other energy alternatives, in addition to the socio-economic benefits and inherent improved supply reliability that are linked to the use of HV networks. In such a scenario, financing new high-voltage interconnectors becomes less of a challenge when supporting policies for reducing harmful carbon emissions and industry standardization are implemented, especially if operation of new coal/fossil-fuel plants is gradually limited [242].

National renewable energy adoption targets are becoming a worldwide trend to battle climate change and pollution in accordance with the 2016 Paris Agreement that was signed by 195 countries [243, 244]. The shift towards more renewable, sustainable sources consequently drives their cost down further. Having said that, the reliance on distributed RES is challenging in densely populated urban areas and major demand centres because of the limited urban energy generation density. This leads to a fast convergence to DERs physical installation network penetration limits [245]. Alternatively, large-scale RES offer a suitable economic alternative to cover the surging demand in the receiving areas. Especially considering the large-scale RES lower normalized cost when compared to small-scale sparse installations with equal cumulative capacity [246-248]. These large-scale sources could be located in very distant locations from load centres based on the relevant technology (i.e. high solar-irradiance area for PV and CSP, and high speed wind area for wind farms). High-Power LCC overhead transmission provides the best option in land-based large scale RES utilization, compared to VSC based XLPE submarine transmission for the growing offshore wind farm demand. The above-mentioned trends are thus considered as the main accelerating factors in increasing the adoption of HV interconnectors. Figure 22 qualitatively summarizes the main HVDC transmission growth factors in the foreseen future.

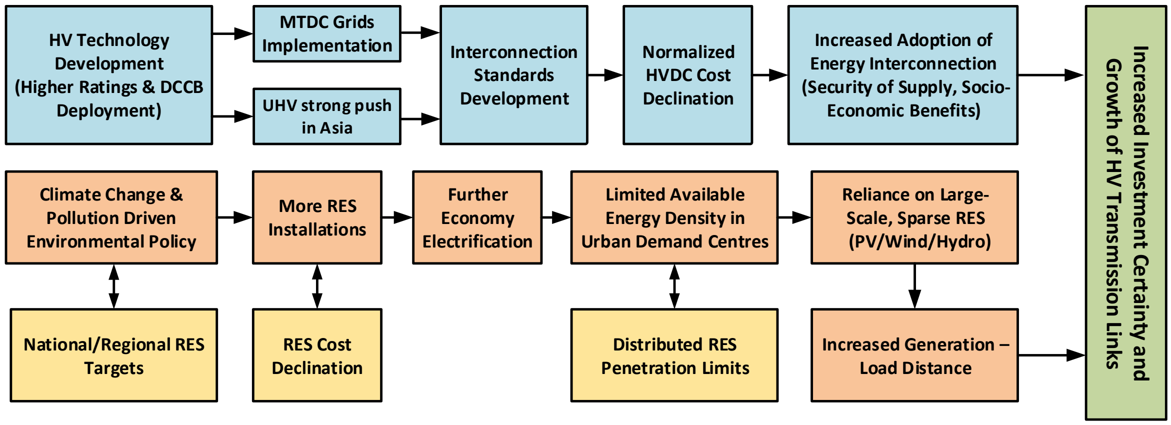


Figure 22: HV interconnection global growth factors.

6. Conclusions

This paper presented a comprehensive overview of HVDC transmission systems, targeting readers from various backgrounds. It provides an up-to-date summary of the HVDC technology options, market status and supplier landscape, challenges and future trends. Furthermore, the main components of HVDC transmission systems and technologies are reviewed, including converters, transformers, transmission assets, control techniques and protection equipment. The main conclusions and observations drawn from the critical reading of the literature, and the qualitative and quantitative analysis in this paper are summarized as follows:

- LCC-HVDC dominates the market in terms of available capacity, mainly contributed by highly rated Asian OH links. Installation costs and DC operating voltages of such systems favour the adoption of OH-HVDC lines over MI-HVDC cables.
- VSC-HVDC transmission technology is beginning to dominate the market in projects rated at 2,000 MW or less and this is expected to continue for the foreseeable future due to its inherently superior technical and grip-support capabilities compared to LCC-HVDC.
- The introduction of MMC type VSC-HVDC transmission systems earlier this decade has facilitated the following for VSCs: scalability to high power and DC voltage, enhanced performance, improved protection capabilities, lower semiconductor losses and reduced filtering requirements.
- XLPE cables market share is surpassing that of its MI competitor (58% of HVDC cables market in 2010s). This trend is dependent on VSC-HVDC development as XLPE cables are mainly compatible with VSCs.

- MTDC networks are expected to play a significant role in future energy transmission networks as they facilitate large-scale renewable energy integration and increase the security of energy supply. However, successful MTDC implementation is dependent on:
  - Developing commercial, reliable, DC protection equipment (DCCB and Fault-Blocking MMC-VSC converters), which are likely to be widespread by 2030.
  - Developing common standards and regulations to integrate existing cross-borders HVDC links operating at different voltages into a single DC network.
- Close coordination between investing bodies in High-Voltage transmission infrastructure and end users should be maintained when building new large-scale HVDC links, to avoid possible under-utilization of HV transmission assets as observed recently in China.

Finally, ambitious visions for global energy interconnection are also discussed and presented as part of the future HVDC transmission systems adoption outlook, fuelled by increased RES utilization targets on country/regional levels.

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