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High Voltage Direct Current (HVDC) Transmission Technology and DC Grids a Comprehensive Review

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Abstract

The evacuation of bulk electrical power over long distances can be done mainly by high voltage alternating current (HVAC) transmission systems. However, where there are large water bodies and long distance between the generation source and demand centres like most islands in European countries, high voltage direct current (HVDC) power transmission is gaining more traction and is proving to be a sustainable solution. Regarding the distance between HVDC and HVAC, the break-even threshold in terms of cost is approximately 600 - 800 km for overhead line systems (OHLs) and 40 - 70 km for systems with cables. The global thirsty to harness the renewable energy sources is diverting the attention towards efficiency and flexibility of power transmission. Traditional HVAC systems are being quickly replaced with HVDC systems in various parts of the world. This report highlights the significance of modern HVDC power transmission networks, topologies, converter varieties, contrasts, and main equipment associated with HVDC systems. Through the use of HVDC converters, renewable energy sources (RES), such as offshore, onshore, coastal wind farms and photovoltaic power plant can be linked to the current existing AC grids. Although the difficulties associated with the upcoming DC grids are also highlighted, the views on multi-terminal HVDC systems and DC grids are also outlined.

Keywords

Multi-Terminal DC Systems, Line-Commutated Converters, HVDC Transmission Systems, Voltage Source Converters, DC Grids

1. Introduction

The growing global demand for electrical energy is pushing the need for larger power plants and advanced transmission systems. Traditional high voltage alternating current (HVAC) networks face congestion and overload issues. High voltage direct current (HVDC) transmission offers significant advantages including no reactive power flow, increased stability, reduced conductor and insulation requirements, and improved efficiency over long distances. However, HVDC also poses challenges such as costly converter stations, complex voltage transformations, and protection difficulties. Various HVDC configurations—monopolar, bipolar, homopolar, and back-to-back—enable flexible power transfer options [1]-[3].

Two main converter types, line commutated converters (LCCs) using thyristors, and voltage source converters (VSCs) based on IGBTs, have distinct benefits, with VSCs gaining traction for new systems thanks to improved control and modular multilevel converters (M2C) [4]. Multi-terminal direct current (MTDC) systems integrate renewable energy sources with AC grids, enabling complex DC grid formations. These emerging DC grids and mega grids present challenges like standardization, fault management, DC breaker development, and power regulation. Continued research focuses on overcoming these to harness the benefits of combined HVAC and HVDC technologies [4] [5].

Methodology and Scope

Numerous HVDC reviews that focus on various facets of technology adoption have been published in the literature. While many studies concentrate on specific system elements such as converter stations, cables, and protective equipment) [2] [6] [8] others compare alternative transmission solutions at the system level in detail e.g., HVAC vs HVDC or LCC and VSC based HVDC [4] [8]-[10]. Furthermore, some assessments focus on the implementation perspective and obstacles of HVDC technologies in a setting that is based on geography and policy framework [11].

However, to the best of the authors' knowledge, a full, step-by-step summary of HVDC technology and outlook on a worldwide scale that integrates academic, practical and operational experiences has not yet been adequately addressed.

As a result, this paper offers an evaluation of the current technologies, ranging from component-by-component to system-level analysis, together with pertinent and well-chosen case studies from various major global projects. The contribution of HVDC to reaching RES goals is also illustrated in the study. In total, 68 literary works are cited in this study, with 65% of them having been published in the previous 5 years. The following is a summary of this paper's primary contributions.

- Comprehensive review of HVDC systems and preferred topologies drawn from real projects and author's critical assessment of existing literature based on their expertise.
- Detailed comparison of HVDC converter types, performance characteristics, trade-offs, and suitability for different applications.
- Multi-terminal HVDC systems and DC grids are also outlined.
- Highlights contemporary issues linked with the forthcoming DC grids in

transmission systems and primary equipment related with HVDC Systems.

This paper is structured as follows: Section 2.0 HVDC Overview, Configurations and Topologies. Section 3.0 HVDC Converter Varieties. Section 4.0 Main HVDC Associated Equipment. Section 5.0 Contemporary issues linked with HVDC grids. Section 6.0 Application Project Cases and Section 7.0 is the Conclusion.

2. HVDC Overview, Configurations and Topologies

High Voltage Direct Current (HVDC) is a system that uses direct current (DC) rather than the more popular alternating current (AC) to transmit electrical power. At the sending end, AC power from the grid is converted into DC using a converter in the rectifier mode. The DC output power of the converter is then transmitted over long distances through HVDC overhead lines or cables. At the receiving end, the DC is converted back into AC using converter operating in the inverter mode, this AC power is fed to the grid which supplies the load, e.g. homes and industries etc.

This technology is increasingly getting popular in modern power systems, especially for connecting renewable energy sources and interconnecting different countries' grids. A typical HVDC system consists of AC switchyard, AC filters, Converter transformer, Converter station, Overhead line or Cable, DC filters and DC switches. The detail description of each HVDC equipment is covered in section 4 of this paper. A simple representation of a HVDC system is shown in Figure 1 below.

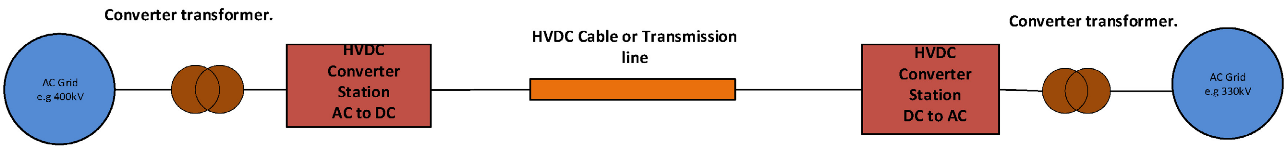

Figure 1. Basic HVDC transmission system representation.

2.1. Advantages of HVDC Transmission

- There is no skin effect with DC power transmission, so the entire conductor size/diameter can be used unlike AC transmission. Conductors used in 50 Hz HVAC transmission systems utilizes skin depth of roughly 9 mm due to skin effect, but that is not the case with HVDC.
- More power transfer capacity is achievable for the same copper size and insulation levels.
- There are no problems with imaginary/reactive power flow or associated losses.
- Bulk power transmission over long distances where AC system would be impractical and/or uneconomic.
- Enables interconnection between power systems which operate at different frequencies.
- Provide more system stability and effective power flow control.

Empirical evidence from case studies shows that using HVDC transmission systems rather than HVAC systems, the transmission system capacity can be boosted by roughly 2 - 3 times [12] [13]. The transmission capacity of a 230 kV (peak 325 kV), 480 MVA HVAC line, for instance, would be 1440 MW if it were converted to an HVDC ±320 kV line [5] [14].

Great-distance transmission of AC power is not possible with the submarine/underground cable; however, it is possible to send DC power at high voltages over great distances. Between 40 - 70 km is the breakeven distance for underground cable. The typical values for capacitive reactance (X_C) and inductive reactance (X_L) for both overhead and submerged cables are displayed in **Table 1**. The provided values make it clear that the cable's capacitance is high (although resistance and inductance can be quite small) that using cables to transmit AC power over extended distances is not possible. On the other hand, DC power flows operate steadily over cable systems, as there are no capacitive effects associated with DC power transmission using cables [15] [16].

Table 1. The typical values of capacitive and inductive reactance for AC 3-Φ, 50 Hz systems per km.

Types of HVAC Transmission line	X_L (Ω)/km	X_C (Ω)/km	$C = \frac{1}{2\pi f X_c}$ (μF)/km
Aerial/Overhead line (OHL).	0.5	30,000	0.106
Underground/Submarine Cable.	0.1	3000	1.061

The comparison of DC and AC transmission is illustrated on the comparison chart in **Figure 2** below.

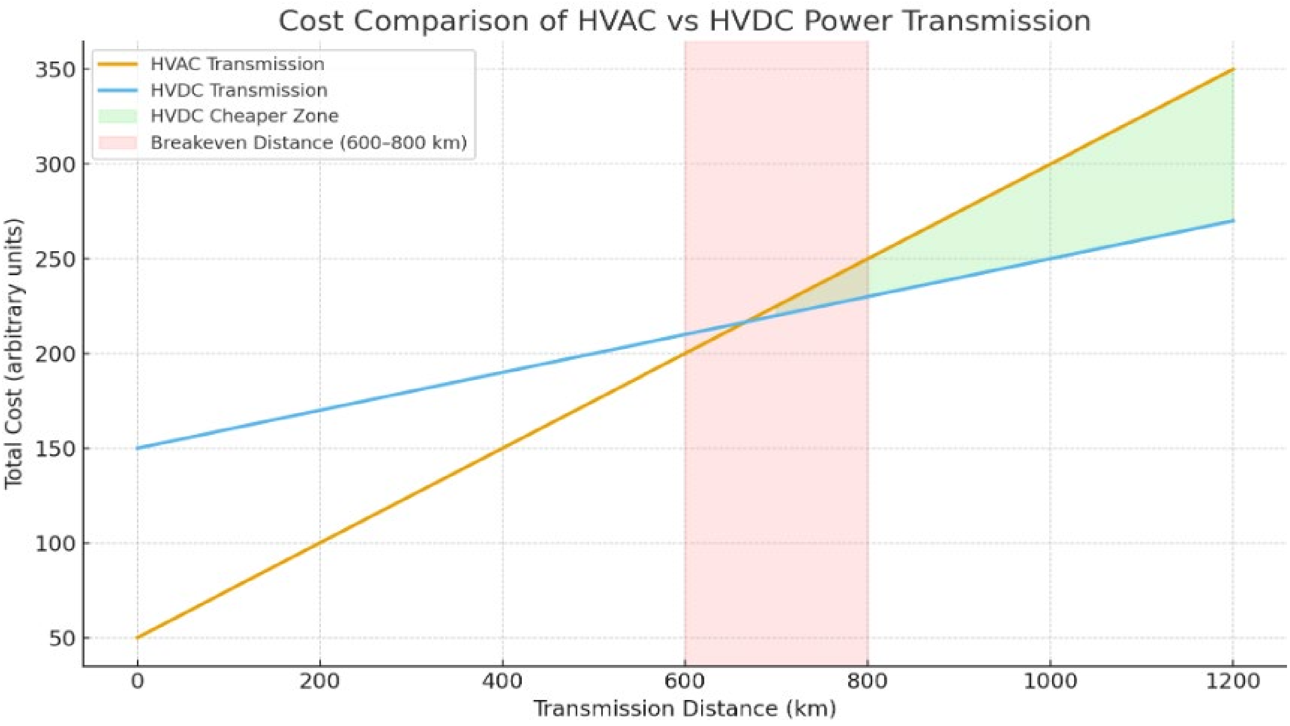

Figure 2. AC and DC transmission system costs in comparison.

The chart shows that AC transmission line costs (yellow) increase with distance, while DC line costs (blue) rise more slowly. The break-even distance, marked around 600 - 800 km, indicates where DC becomes more cost-effective than AC due to its lower line and loss costs. Hence, AC is cheaper for shorter distances, but DC is more economical beyond this point, highlighting the advantage of DC for long-distance power transmission.

2.2. HVDC Configurations

Different topologies for HVDC networks are determined by the type of ground connection or return path, the layout of transmission line connections, and the choice of transmission line polarity. Below is a detailed examination of various design sections [17].

2.2.1. Monopolar HVDC Link Design

In a monopolar design, electricity is transmitted via a single conductor and either the ground (earth) or the sea provides the return path using electrodes at either station. This design provides the network with the lowest cost because only one conductor line is needed for power transmission. At the same time, it is vulnerable to DC faults. It will experience transmission power loss during a fault state, until the fault is resolved and the supplies restored. Monopolar HVDC designs were used only for low power rating and cable transmission.

Another version of a monopole HVDC system, is the one with a dedicated metallic return, it comprises of a single conductor through which power is transmitted, while a dedicated return path is used for returning the current. A metallic return conductor in a high voltage direct current system is not fully insulated to the transmission voltage but insulated to a lower level than the pole and is grounded at one end of the system and floating at the other end. This is different from bipolar systems, which use two conductors (one positive and one negative) [2] [15] [17]. **Figure 3** shows the Monopolar HVDC link Design.

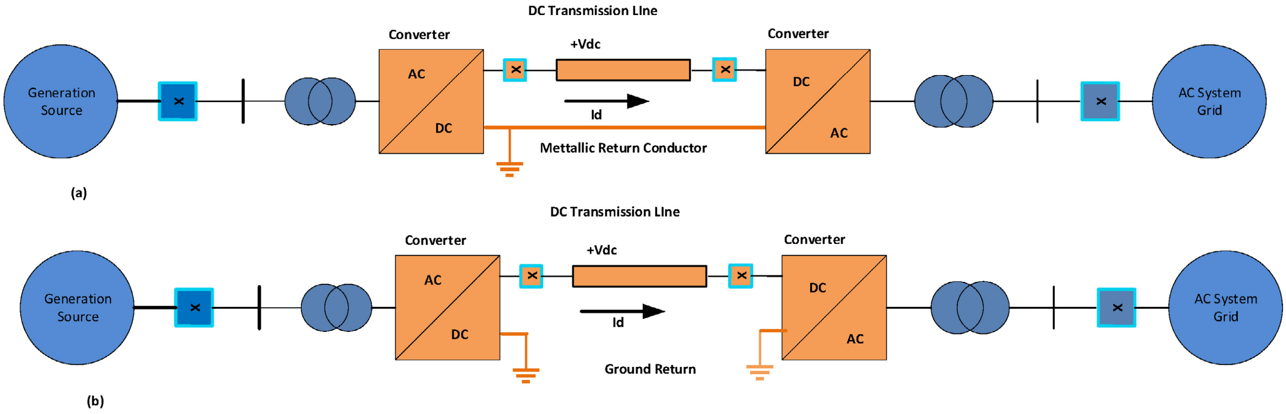

Figure 3. Simplified diagram of monopolar HVDC link design with (a) dedicated metallic return, (b) ground return.

In some cases, the monopolar links installed earlier are converted into bipolar systems by adding additional substation pole and transmission pole. In recent schemes, earth return is becoming less common because of environmental impact making this type of design less popular. However, there are certain designs which make a transition from bipolar to monopolar operation after a fault developing or when the other pole is out for maintenance [18]. In this case, the pole conductor of the disconnected converter is reconfigured for use as a metallic return.

A good example is the NordLink HVDC interconnector between Norway and Germany, the main operating mode is bipolar operation, but each pole can run in monopole operation to allow certain preventive maintenance and corrective repair work of the other disconnected pole. This is one typical good monopolar application in real projects and is coming with this modification and thereby bringing in the system redundancy, efficiency and reliability in power transmission network.

2.2.2. Symmetrical Monopole HVDC Link Design

A variation of a monopolar configuration which utilises two high voltage conductors at opposite polarity, that operate at half the transmission voltage is called a symmetrical monopole. The ground connection can be made at several locations in this design. The DC link capacitors' centre point is the ideal location for the ground connection. With V_{dc} being the nominal pole-to-pole DC value, the steady state voltage for each pole is therefore equal to half of the converter's nominal DC voltage, such as $\frac{+V_{dc}}{2}$ or $\frac{-V_{dc}}{2}$.

A good example of symmetrical monopole application is the new Caithness-Moray-Shetland multi-terminal HVDC link that uses the Voltage Source Converter (VSC) technology [9] [19].

2.2.3. Challenges with Monopole Applications

HVDC monopole systems relying on ground return face criticism for ground potential rise, corrosion, electromagnetic interference, and environmental impacts, leading to restrictions in some regions. They transmit only half the power of a bipolar system at the same voltage and current, limiting capacity. Monopoles lack redundancy: any converter or cable failure causes full system shutdown, unlike bipolar systems that can operate at half capacity. Additionally, ground return paths cause higher line losses [17] [20].

The criticism of a monopole HVDC system with ground return gave birth to the symmetric monopole, and asymmetric monopole with metallic return. The environmental regulations and other stakeholders may prevent construction of an HVDC project which would solely want use the ground as a return path and permission for installing the electrodes and continuous ground current maybe difficult to secure from regulators.

2.2.4. Bipolar HVDC Link Design

This kind of design consists of two conductors, or a set of conductor lines, one of which is negatively charged and the other positively charged connected to an independent converter. The voltage amplitude of both lines is equal, but opposite polarity. More flexibility and redundancy in terms of power transmission continuity is provided by this design [20]. Even if one conductor line is out of service due to fault or maintenance, the other line will still function on its own as a monopolar link and may occasionally be loaded with twice its rating if the conductor and converter station are designed for such a loading capability. Figure 4 below shows the rigid bipolar HVDC. The earth point of the rigid bipolar HVDC system is set at a single point in each station. The BritNed Interconnector, is a bipolar HVDC link between Great Britain and the Netherlands. Compared to a monopole with metallic return, bipolar design is more expensive since both conductors need to be insulated for the full voltage. Bipolar transmission does have a number of benefits, though, which can make it a desirable option in many recent projects such as the above.

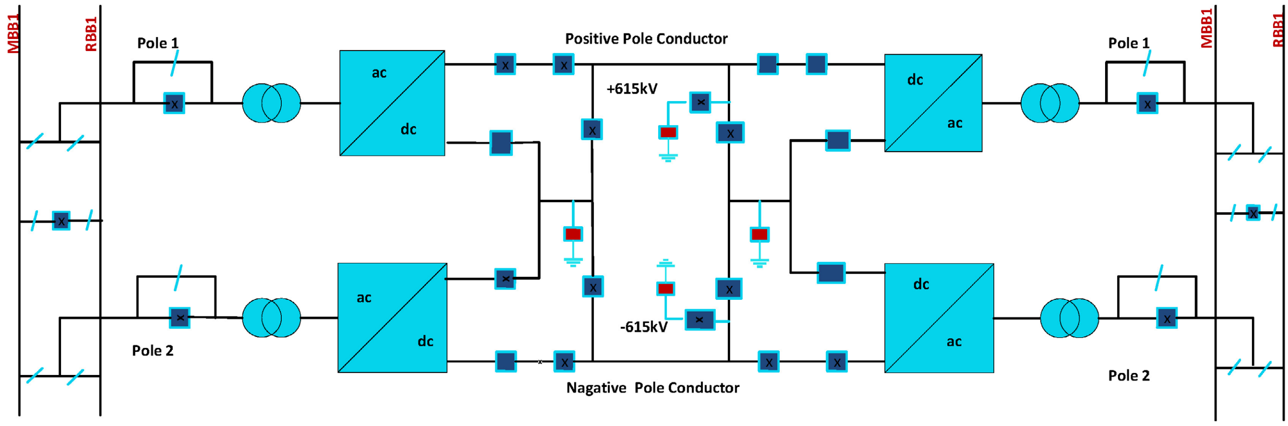

Figure 4. Simplified diagram of a Rigid Bipolar HVDC transmission system Design.

2.2.5. Bipolar with a Dedicated Metallic Return (DMR)

A bipolar HVDC link with a dedicated metallic return (DMR) is a power transmission system that uses a metallic return shared between two poles. The DMR is insulated to a lower level than the pole and is usually grounded at one converter station. The bipolar with DMR can be operated as an asymmetric monopole in the event of a pole-to-ground fault. Figure 5 below illustrates a Bipolar with a dedicated metallic return (DMR).

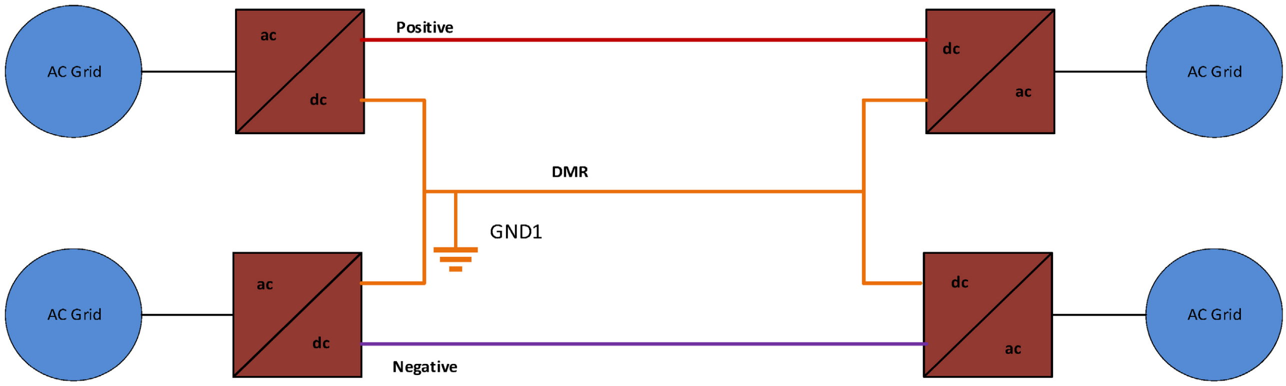

Figure 5. Simplified diagram of Bipolar with a dedicated metallic return (DMR).

The 1305 km HVDC Champa–Kurukshetra transmission link in India is an example of a bipolar project with a dedicated metallic return (DMR). The project uses a DMR instead of a conventional ground return which runs on the same tower as the pole conductors.

2.2.6. Challenges with Bipolar HVDC Applications [21]

Bipolar HVDC systems, while offering up to 50% transmission redundancy during single pole-to-ground faults, face challenges in precise fault discrimination due to similar electrical characteristics of pole-ground and pole-DMR faults. Control complexity arises from managing two poles and maintaining operation during pole failures via monopolar modes. Higher installation and maintenance costs stem from more equipment requirements, including dual converters and protection systems. Grounding systems must safely handle excess load during faults, with failure risking damage or hazards

Despite all these challenges, bipolar HVDC designs offer more benefits like higher efficiency over long distances, reduced line losses, more precise control over power flow, redundancy and reliability. The setbacks mentioned above are often addressed through careful planning, advanced technology, and redundancy systems.

2.3. Transmission Topologies for HVDC

2.3.1. Back-to-Back HVDC Link

Back-to-Back HVDC links are normally used to connect asynchronous AC grids (grids that operating at different frequencies). The two converters (rectifier and inverter) are located at the same site/location. They don’t have long transmission line or cable; they are usually connected by short section of busbar.

2.3.2. Point-to-Point HVDC Link

Point-to-Point HVDC links are HVDC systems that transmit power over long distances between two specific points, e.g. connection of offshore wind generation to the Grid or connection between two substations in the network. This arrangement consists of a converter in the rectifier mode at the sending end and another converter in the inverter mode at the receiving end directly connected by either overhead line or cable. Most commercially operating HVDC links are point-to-point, however, with the increasing integration of renewable energy generation and interregional connection interests, multi-terminal HVDC systems are gaining popularity.

2.3.3. Multi-Terminal HVDC Systems

Multi-Terminal HVDC (MTDC) systems are advanced high-voltage direct current networks that connect multiple power sources and receiving ends through a shared DC transmission grid. They are increasingly used for integrating renewable energy, enhancing grid reliability, and enabling efficient long-distance power transfer. Unlike traditional point-to-point HVDC systems, MTDC systems connect more than two terminals, allowing multiple sources (e.g., offshore wind farms) to supply power to multiple receivers [2].

a) Why Multi-Terminal HVDC systems instead of point-to-point links?

Multi-Terminal HVDC (MTDC) systems present transformative advantages compared to traditional two-terminal, point-to-point HVDC links by enabling multiple terminals to interconnect within a single DC grid, thereby offering multi-directional power flows, enhanced resilience, and more flexible resource integration. Unlike point-to-point links, MTDC systems establish a network capable of dynamic power flow control among various terminals, which significantly improves operational flexibility and system reliability. This advanced topology supports complex power exchange, allowing for better grid resilience as the mesh configuration provides multiple pathways for power transmission, ensuring continued operation even during faults or maintenance of individual components [22].

MTDC systems offer major scalability advantages for grid expansion as they allow modular growth through adding converter stations and DC lines without disrupting existing infrastructure. Unlike rigid point-to-point HVDC links, MTDCs support hybrid solutions integrating FACTS devices like STATCOMs for enhanced reactive power compensation and voltage stability [23]. Their active power flow control optimizes congestion management, enabling efficient regional power exchanges and flexible energy trading.

Moreover, MTDCs facilitate cross-border interconnections between asynchronous grids, supporting international energy exchange and ancillary services that traditional point-to-point HVDC cannot easily provide [22].

b) Multi-Terminal HVDC Projects.

The three multi-terminal HVDC projects detailed in Chapter 6 illustrate key advancements in HVDC technology: The Wudongde ±800 kV link in China transmits 8000 MW of hydropower using hybrid converters over 1452 km. The Zhangbei ±500 kV MTDC system integrates wind, solar, and pumped storage to supply Beijing with stable renewable power; and the Caithness-Moray-Shetland ±320 kV link, Europe's first multi-terminal HVDC, connects Shetland to Great Britain's grid, enabling 1200 MW renewable integration. These projects highlight scalable, flexible, and efficient HVDC grid solutions for diverse energy needs

2.4. Regional, Interregional and Pan Continental HVDC Grids

Regional DC Grids: A Regional DC Grid is a direct current (DC) power network that connects multiple locations within a specific geographic region. It is designed to efficiently transmit and distribute electricity using DC technology, which offers several advantages over traditional AC grids in certain applications. A typical regional DC grid is often defined as a system that consists of one protection zone for DC earth faults. This means that within the regional DC grid, all components—such as converters, DC cables, and DC substations—are within the same fault protection boundary [24].

Interregional DC Grids: These are possible to build today, and some projects are already in development or operation. These grids would connect different regions, countries, or even continents using High Voltage Direct Current (HVDC) transmission technology [25].

2.4.1. Key Characteristics of a Regional DC Grid Protection Zone

A Regional DC Grid Protection Zone unifies the DC grid under a single fault-clearing strategy, promptly detecting and isolating any earth or ground faults within its boundaries to prevent fault propagation and enhance stability. Protection devices like DC switches and relays are coordinated to isolate faults selectively, minimizing disruption and maintaining power to unaffected areas, often using fast-acting solid-state switches or converter-based fault ride-through. These zones operate typically within Medium or High Voltage DC levels and use multi-terminal configurations, adopting either point-to-point or meshed topologies, influencing protection complexity and grid robustness while supporting flexibility and scalability in the DC grid.

2.4.2. Examples of Existing & Planned Interregional DC Grids [26]

- China's UHVDC network: Transmits power over 3000+ km from western renewable energy zones to the east.
- Europe's Super grid: A proposed DC network to interconnect European countries and integrate offshore wind.
- Asian Super Grid (Japan-Korea-China-Mongolia-Russia interconnection): A vision for intercontinental HVDC links.
- Sun Cable (Australia-Southeast Asia HVDC project): A planned 3800 km undersea HVDC cable from Australia to Singapore.

3. HVDC Converter Varieties

There are two main types of converters used in HVDC schemes worldwide namely Line Commutated Converter (LCC) and Voltage-Source Converter (VSC). The major commercial suppliers of the HVDC converters are Siemens, Hitachi Energy, General Electric (GE, USA), Mitsubishi Electric (Japan), Dongfang Electric Corporation (China) and Alstom etc. The following lists the primary varieties of HVDC converters [4] [5] [9].

3.1. The Line Commutated Converters (LCCs)

Often known as Current Source Converters (CSCs), these devices use thyristors as switching elements. Natural line commutation is necessary for these converters to function. These converters find widespread use in commercial HVDC installations worldwide. In Europe, the largest LCC scheme is the Western Link in UK, commissioned in 2018 rated at 2250 MW at ±600 kV. This link comprises of two LCC Converter stations, one at Hunterston western Scotland and another at Flintshire Bridge (Deeside) in North-East of Wales [27].

3.1.1. Basic Principle of Current Source Converters

Why are they called Line Commutated Converters (LCCs)?

They are called Line Commutated Converters (LCCs) because the switching device (thyristor) relies on the AC line voltage to turn off or "commutate" the current from one device to the next. Once a thyristor is triggered on by a gate pulse, it remains conducting as long as current flows. It cannot be turned off by a control signal but turns off naturally when the AC current crosses zero, which happens every cycle due to the AC waveform. This line-voltage-dependent turn-off mechanism gives LCCs their name, as commutation is performed by the AC line itself rather than by forced electronic control.

Due to this property thyristors are widely used in HVDC converter stations, AC voltage controllers, and phase-controlled rectifiers [28]. The power circuit diagram for the three-phase fully controlled current source converter consists of six thyristors is shown in **Figure 6** below. The output of this converter has six pulses per cycle of input supply. Hence it is also called a three-phase six-pulse converter. It has three legs or arms of thyristors,

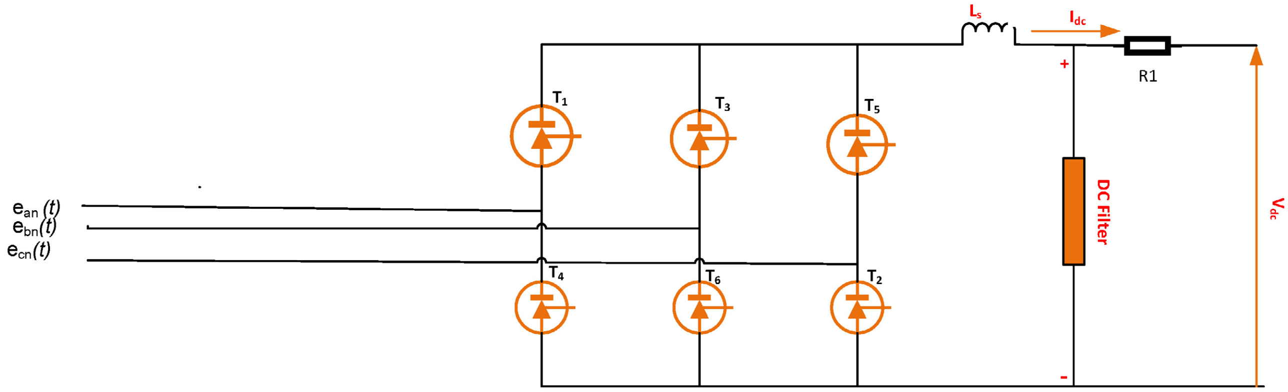

Figure 6. Basic structure of current source converter.

If the thyristor firing angle, $\alpha = 0$, then the DC voltage of the converter is given by:

$$V_{dc} = \frac{1}{\pi/3}\int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \sqrt{2}\cdot V_{LL}\cdot\cos(wt)\,\mathrm{d}(wt) = \frac{3\sqrt{2}}{\pi}V_{LL}\left[\sin(wt)\right]_{-\frac{\pi}{6}}^{\frac{\pi}{6}} = \frac{3\sqrt{2}}{\pi}V_{LL} \qquad (1)$$

Where: V_{LL} = Line-to-line RMS voltage.

This is known as no-load DC voltage of the converter, V_{do}. Now adding a thyristor firing angle, α, which is the same for all 6 switches, *i.e.* controlled firing of thyristors.

$$V_{dc} = \frac{3}{\pi}\int_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} \sqrt{2}\cdot V_{LL}\cdot\cos(wt)\,\mathrm{d}(wt) = \frac{3\sqrt{2}}{\pi}s\left[\sin(wt)\right]_{-\frac{\pi}{6}+\alpha}^{\frac{\pi}{6}+\alpha} = \frac{3\sqrt{2}}{\pi}V_{LL}\cos\alpha \qquad (2)$$

Equation 1 above defined, $\frac{3\sqrt{2}}{\pi}V_{LL} = V_{do}$.

Therefore,

$$V_{dc} = V_{do}\cos\alpha \qquad (3)$$

where: V_{do} = Maximum DC voltage (ideal, no overlap).

Equation 3 illustrates that the converter DC voltage is proportional to the thyristor firing angle. As α increases, V_{dc} decreases, i.e greater the delay, smaller the output voltage

When α = 0 → diode bridge $V_{dc} = V_{do}$.

$0 \leq \alpha < 90$→ rectifier $V_{dc} > 0$.

$\alpha = 90$→$P = 0$ $V_{dc} = 0$-current reversal is not possible.

$90 \leq \alpha < 180$ → $V_{dc} < 0$ Therefore inversion (inverter)-necessary for the negative pole.

3.1.2. Commutation Overlap

Commutation overlap refers to the period during which two switching devices (such as thyristors or diodes) conduct simultaneously during the transfer of current from one phase to another. This occurs due to the inductance present in the AC system, *i.e.*, commutation reactance, which causes a delay in the full transfer of current from the outgoing valve to the incoming valve.

Considering adding a source inductance $L_c \neq 0$ see illustration on **Figure 7** below.

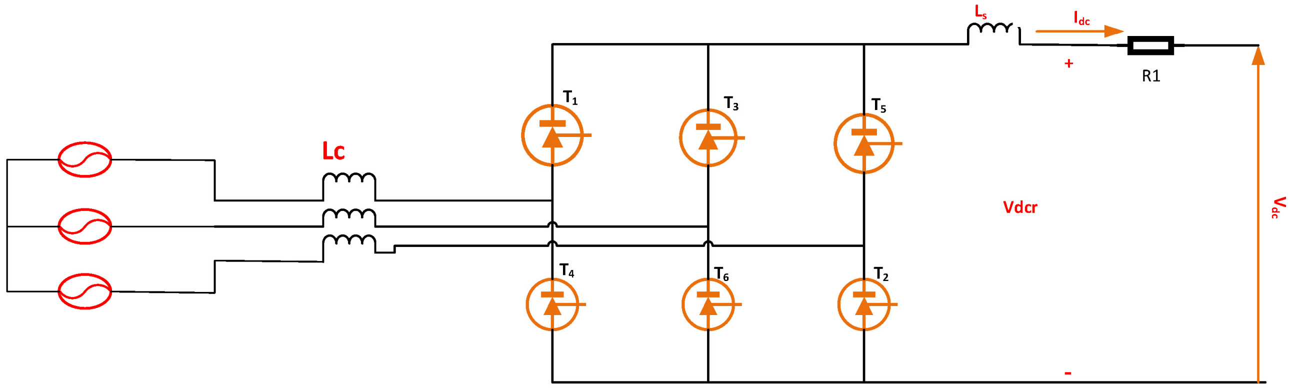

Figure 7. Commutation overlap circuit.

Average DC Voltage with Overlap

Recall $V_{LL} = \sqrt{3}V_{\phi}$; $E_m = \sqrt{2}V_{\phi}$ & $V_{do} = \frac{3\sqrt{2}}{\pi}V_{LL}$.

Therefore,

$$V_{do} = \frac{3\sqrt{2}}{\pi}V_{LL} = \frac{3\sqrt{6}}{\pi}V_{\phi} = \frac{3\sqrt{3}}{\pi}E_m \tag{4}$$

where:

- V_{do} = maximum theoretical DC output voltage (no-load voltage).
- E_m = peak line to neutral voltage.
- V_{ϕ} = line-to-neutral rms voltage.
- V_{LL} = line-to-line rms voltage.

$$\begin{aligned} V_{dc} &= \int_{\alpha}^{\alpha+\mu}\frac{3}{2}E_m\cos\theta\cdot \mathrm{d}\theta + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}}\sqrt{3}E_m\cos\left(\theta-\frac{\pi}{6}\right)\cdot \mathrm{d}\theta \\ &= \frac{3\sqrt{3}}{2\pi}E_m\left[\cos\alpha+\cos\left(\alpha+\mu\right)\right] \end{aligned} \tag{5}$$

In terms of V_{do},

$$V_{dc} = \frac{V_{do}}{2}\left[\cos\alpha + \cos\left(\alpha + \mu\right)\right] \tag{6}$$

where:

- ❖ α is the thyristor firing angle,
- ❖ μ is the overlap angle.

When μ increases due to high system inductance (commutation reactance), the term cos (α + μ) becomes smaller, leading to a reduction in DC voltage. Larger overlap μ causes a drop in DC voltage, leading to lower power transfer efficiency. Therefore, when commutation overlap μ is included, the effective DC voltage is reduced.

Average DC Current during Commutation Overlap.

The firing delay adds a phase shift to the current, which is always lagging the voltage, and $\cos\alpha = \cos\phi$.

Considering the fundamental component of current:

$$i_{pk} = \frac{2}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} i_a \cos\left(\theta\right)\cdot \mathrm{d}\theta = \frac{2I_{dc}}{\pi}\int_{-\frac{\pi}{3}}^{\frac{\pi}{3}} \cos\left(\theta\right)\cdot \mathrm{d}\theta = \frac{2\sqrt{3}}{\pi} I_{dc} \tag{7}$$

$$I_{1rms} = \frac{\sqrt{6}}{\pi} I_{dc}$$

Average DC Output Current.

$$i_1\left(t\right) = \frac{2\sqrt{3}}{\pi} I_{dc} \cos\left(\omega t - \alpha\right) \tag{8}$$

During Overlap Interval

$$I_{dc} = I_c = \frac{\sqrt{3}E_m}{2\omega L_c} = \frac{V_{LL}}{2X_c} = \frac{\pi V_{do}}{6X_c} \tag{9}$$

$i_3\left(t\right) = I_c\left(\cos\alpha - \cos\omega t\right)$ with $\alpha \le \omega t \le \alpha + \mu$.

Average current is: $I_{dc} = I_c\left[\cos\alpha - \cos\left(\alpha + \mu\right)\right]$ where $\omega t = \alpha + \mu$ at the end of the commutation interval. The DC current depends on the difference between cosine terms of the firing angle and overlap angle. The overlap angle μ is related to the system inductance L_c, the DC current I_{dc} and the short-circuit current I_c. As μ increases, the term cos (α + μ) gets smaller, meaning the current output also decreases.

Equation (9) above represents the maximum possible short-circuit current that can flow in the system. It shows that the short-circuit current is inversely proportional to the commutation reactance (X_c). As X_c (or system inductance L_c) increases, the short-circuit current decreases, making commutation more difficult.

Table 2 below shows the summary of equation.

In LCC, the power flow can be reversed by changing the DC voltage's polarity. Controlling the firing angle of the grid pulses allows the converter bridges to function as both an inverter and a rectifier. DC voltage control is obtained by controlling either the magnitude of the applied AC voltage V_m or the firing angle α. It is critical to realize that firing angle is the single control variable that differentiates output.

Table 2. Equation summary.

Equation	Explanation	Explanation
$V_{dc} = \frac{V_{do}}{2}\left[\cos\alpha + \cos\left(\alpha + \mu\right)\right]$	DC voltage with overlap	Overlap angle (μ) reduces DC voltage.
$I_{dc} = I_c\left[\cos\alpha - \cos\left(\alpha + \mu\right)\right]$	DC current with overlap	Overlap angle (μ) reduces DC current.
$V_{do} = \frac{3\sqrt{2}}{\pi} V_{LL}$	Ideal no-load DC voltage	Maximum DC voltage with no overlap.
$I_c = \frac{\sqrt{3}E_m}{2\omega L_c} = \frac{V_{LL}}{2X_c} = \frac{\pi V_{do}}{6X_c}$	Short-circuit current	Higher commutation reactance (X_c) reduces current and increases overlap.

Because the AC current is switched in discrete steps (instead of continuously) in Figure 6 set up, it constitutes harmonic components in addition to the fundamental frequency. The harmonics generated in a six-pulse rectifier (most common LCC configuration) are of the order:

$$h = 6n \pm 1,\ n = 1, 2, 3, \cdots$$

This means harmonics appear at frequencies like 5th, 7th, 11th, 13th, etc. of the fundamental frequency. These harmonics cause voltage distortions, heating in transformers, and electromagnetic interference (EMI) in power systems [27] [28].

Both the rectifier and the inverter terminals in LCC draw reactive power because the current at both terminals is lagging the voltage. Due to line commutation, current must lag the corresponding voltage because each silicon controlled rectifier (SCR) can only delay the initiation of current with respect to the zero crossing of the AC voltage, *i.e.*, the thyristor must forward-bias before current can flow. This results in lagging power factor operation on both rectifier and inverter sides [22] [23]. Therefore, LCC-based converters are reactive sinks and require capacitive compensation.

LCC terminal placement within an AC network is usually limited to only firm/strong buses, *i.e.*, buses that have low impedance, high short-circuit power, and stable voltage. Such grid connection points ensure that reactive power sources will be close and therefore capable of providing the reactive power support necessary for the LCC terminals [29]. Harmonic filters are also necessary to enhance the waveforms of AC current and they can play a dual responsibility of partially supplying the reactive power that the converter needs as well as smoothening the voltage waveforms from harmonics.

Despite its excellent historic performance, high reliability, and low cost, the LCC converter is somewhat difficult for offshore applications because of its huge footprint, which is caused by the requirement for substantial filters and reactive power compensation equipment surrounding it. There is still more room for research to remove and eliminate or minimise the reactive power compensating equipment requirements surrounding the LCC technology and researchers are working on that [1].

This limitation in LCC technology makes the Voltage Source Converters more favourable as they are capable of both supplying and absorbing reactive power from the system due to their added control capability. Being voltage control devices themselves, their terminal positions don't have to be restricted to rigid areas of the network. This is a clear advantage of the VSC technology over LCC in HVDC systems.

Recent developments in LCC technology have seen researchers working on a hybrid commutated converter (HCC) replacing traditional thyristors with reverse blocking integrated gate commutated thyristors (RB-IGCT). HCC-HVDC converter based on RB-IGCT can mitigate commutation failure (CF) under extremely weak network conditions. Furthermore, they can potentially reduce the reactive power demand of the convertor [30]. Enhanced power reversal control strategies allow the use of hybrid LCC/ full-bridge VSC systems which enable online power flow reversal [31]. An example of the hybrid systems are Wudongde and Skagerrak projects covered in Section 6.

3.2. The Voltage Source Converters (VSCs)

In the heart of the VSCs are the Insulated Gate Bipolar Transistors (IGBTs), these are hybrid semiconductor device comprised of two or more solid state devices. In particular, the IGBT combines the high switching speed of a metal-oxide-semiconductor field-effect transistor (MOSFET) with the high current-carrying capability of a Bipolar Junction Transistor (BJT). Its wide application in power electronics is found in Voltage Source Converters (VSCs), motor drives, and renewable energy systems.

An IGBT does not inherently conduct reverse current efficiently, hence a freewheeling (antiparallel) diode is placed across the IGBT. This diode conducts reverse current when the IGBT is off, this reduces losses in applications requiring bidirectional current conduction [32].

Where does the name Voltage Source Converters originate from? The VSC maintains a constant directionality of the DC-side voltage, to preserve continuity and smooth voltage. A large capacitor is placed in parallel with the DC-side of a VSC, giving the impression that the DC-side is a voltage source rather than a current source [33]. The name voltage source converter is based on this phenomenon and this happens because the change in capacitor voltage is slowly and very stiff, the DC bus behaves like a voltage source.

Why the Capacitor Makes the DC Side Appear as a Voltage Source? The rate of voltage change across a capacitor is given by the equation: $I = C \cdot \frac{\mathrm{d}V}{\mathrm{d}t}$. Since the capacitor is large, $\frac{\mathrm{d}V}{\mathrm{d}t}$ is very small, meaning that even when current varies, voltage remains nearly constant. This makes it appear as if there is a stable DC voltage source at the output. **Figure 8** below shows the basic structure of voltage source converter

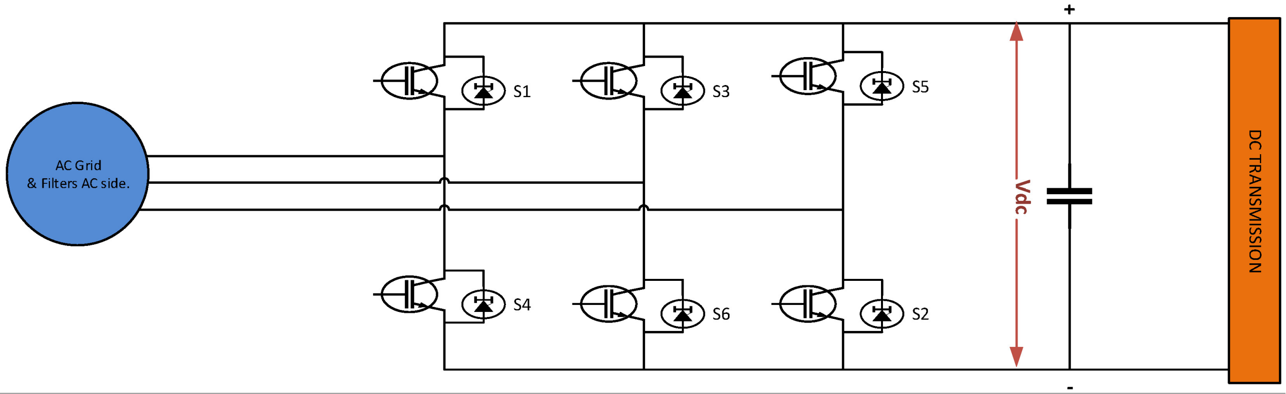

Figure 8. Basic structure of voltage source converter.

Unlike the traditional line-commutated converters that require the AC system's voltage waveform to naturally force the current to zero for commutation (switching off the device), the VSC is self-commutated, meaning it does not rely on external AC voltage for switching off. Instead, it uses semiconductor switches like IGBTs, MOSFETs, or Gate Turn-Off Thyristors (GTOs), which can be turned on and off by an external control signal [3].

The active-reactive (P-Q) operating range for a VSC shows it can operate in all four quadrants of the active-reactive power plane which is one of its strength compared other technologies like LCC [34]. This four quadrant operation enables the VSC to independently control both active (real) and reactive power at both ends of the DC transmission, making it highly suitable for applications like HVDC (High Voltage DC) transmission, FACTS (Flexible AC Transmission Systems), and renewable energy integration. **Figure 9** below shows the P-Q operating range of the Voltage Source Converter.

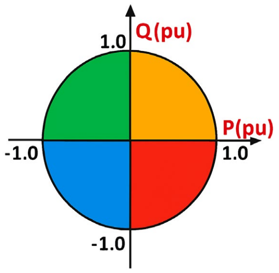

Figure 9. The P-Q diagram of voltage source converter operating range.

The VSC employs Pulse Width Modulation (PWM) switching technique to generate its own control AC waveform making it independent of the grid voltage. This signal from PWM control system sends signals to turn switches on or off precisely, allowing precise voltage and current wave-shaping and this makes the VSC highly controllable. VSCs have control capabilities that are not possible with thyristors in LCCs since IGBTs can be turned on and off using PWM control signals [35].

Reactive power can be supplied and used by VSCs due to their control capabilities. Since they are voltage control devices, their terminal positions don't have to be restricted to rigid areas of the network. Thus, the converters can be placed anywhere in the AC network. This is a clear advantage of VSC-based HVDC technology over LCC [25].

The converter can be used to create a balanced set of three-phase voltages, similar to a virtual synchronous generator, and energize the network from zero voltage [grid formation]. The grid-forming inverter maintains an internal voltage magnitude phasor, with the magnitude and frequency set locally at each inverter. Thus, a grid-forming inverter acts like a sinusoidal voltage source [36]. Forced (self) commutation with VSC even allows for black start. The sending and receiving end AC systems' voltage stability and transfer capacity are enhanced by the dynamic support of the AC voltage at each converter terminal [4] [25]. The 2-level and 3-level converters are examples of VSC technology, which uses PWM based on high switching frequency to produce output waveforms that are sinusoidal. These converters can behave like a universal generator having the properties of DC generators and AC synchronous generators [37].

3.2.1. Why Are They Called 2-Level and 3-Level

a) 2-Level VSC

A 2-level Converter can generate only two voltage levels at the output.

$\frac{+V_{dc}}{2}$ (positive DC bus voltage) and $\frac{-V_{dc}}{2}$ (negative DC bus voltage).

The notation—"2-level converter" is derived from description of the output voltage levels relative to the DC bus

This Converter type uses six IGBT switches in a three-phase (3ϕ) bridge topology and the output waveform is a square wave (high harmonic content). Requires Pulse Width Modulation (PWM) to approximate to a sine wave.

b) 3-Level VSC (Neutral Point Clamped—NPC)

A 3-level Converter generates three voltage levels at the output:

$\frac{+V_{dc}}{2}$ (positive DC bus).

0 V (neutral or midpoint voltage).

$\frac{-V_{dc}}{2}$ (negative DC bus).

The 3-level Converter typical uses 12 IGBT switches and additional clamping diodes (hence, sometimes it's called NPC or Neutral Point Clamped Converter). Produces a waveform closer to a sine wave with lower harmonics and requires less filtering compared to 2-level VSC.

3.2.2. The Modular Multilevel Converters (M2Cs)

This subtype of VSC system was created and produced to address the shortcomings of two-level and three-level VSC systems. The characteristics of behind Modular Multilevel Converters (M2C) include the ability to add several DC capacitor sources to produce an AC output waveform. These can be turned on at higher frequencies via PWM control, which uses multiple kHz frequencies or at power frequency to reduce switching losses, harmonic content, and filter needs [38]. **Figures 10** shows the M2C topology.

These converters also have the following additional benefits: minimal dv/dt stress, modularity, redundancy, and simple maintenance. The principle behind M2Cs compared to Two-Level Converters lies in their ability to generate high-quality multilevel voltage waveforms with improved efficiency, scalability, and reduced harmonic distortion [12].

a) Fault Handling in Modular Multilevel Converters.

When a submodule (SM) fails in a Modular Multilevel Converter, the system can bypass or replace the faulty SM to ensure continued operation. The behaviour depends on the type of failure (open-circuit or short-circuit) and the fault management strategy implemented. If a SM fails, a bypass switch (or redundant SMs) is activated to remove the faulty unit, converter continues operating with one fewer submodule per arm and this may slightly reduce the voltage level but maintains operation. After bypassing a faulty SM, the capacitor voltage balancing algorithm adjusts the remaining SMs to maintain suitable output voltage levels. Therefore, a single SM fail, has minimal impact to the converter operation.

Figure 10 below shows the topology of the Modular Multilevel Converter.

In case of multiple SMs failing, the converter can still operate but may experience higher voltage ripples and require increased compensation from other SMs. With too many SMs failing, the system might shut down to protect itself or require manual intervention to replace the faulty submodules. This fault-tolerant design is one of the biggest advantages of M2Cs over traditional two-level and three level converters. These converters are utilized in a large number of commercial HVDC projects worldwide like the North-Sea-Link project, between Norway and England [3].

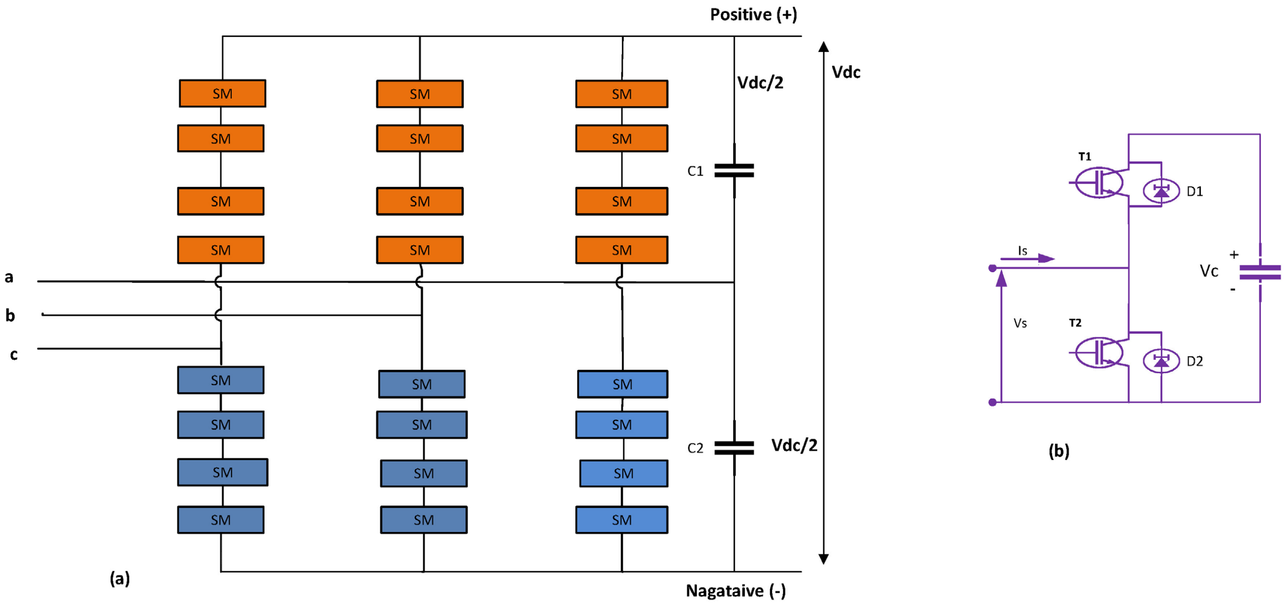

Figure 10. Modular multilevel converter (M2C) (a) topology, (b) inside a submodule (SM).

b) Hitachi Energy's HVDC Light technology Modular Multilevel Converter (M2C).

Hitachi Energy's HVDC Light technology, featuring the Modular Multilevel Converter (M2C), is a leading Voltage Source Converter (VSC) system designed for underground, underwater, and long-distance power transmission. It supports power capacities up to 3000 MW (with some developments reaching 3500 MW to 4800 MW) and voltage ratings up to ±640 kV, with converter transformers rated up to 1500 MVA and 500 kV. Its key technical features include bi-directional power flow for quick reversal, active/reactive power control for grid support functions such as voltage and frequency regulation, black start capability, and STATCOM functionality. The compact design results in smaller converter stations, enabling installation in space-constrained locations.

HVDC Light technology also boasts exceptionally low electrical losses, environmental benefits such as oil-free cables and neutral electromagnetic fields, and fast installation and commissioning times. It has been widely deployed in numerous projects globally, with a strong track record in Europe and beyond [39]-[41].

3.3. Comparison of VSC-Based and LCC-Based HVDC Converter Systems

A comparison of VSC-based and LCC-based HVDC converter systems is shown in Table 3 below.

Table 3. Comparing voltage source converters (VSCs) and line-commutated converters (LCCs).

Characteristic	Line-Commutated Converters (LCCs)	Voltage Source Converters (VSCs)
Switching Devices (Valves)	Thyristors (SCRs)	IGBTs, GTOs, or MOSFETs
Commutation Type	Line-commutated (requires AC source). Can turn on only	Self-commutated (can operate without AC source). Turn on and off
Control	Only controls active power (P). Simpler control due to natural commutation	Controls both active (P) and reactive power (Q). Complex control due to self-commutated
Power Flow	Typically bidirectional but requires special control for inversion (based on reversing polarity of DC voltage-DC current direction remains constant)	Fully bidirectional-easy power reversal (based on reversing the direction of DC current flow to change power direction, keeping the DC voltage polarity constant)
Reactive Power	Consume reactive power, require capacitive compensation	Can absorb or generate reactive power independent of active power
Harmonics	Produces high harmonics; requires large AC filters	Lower harmonics due to PWM control. Can be negligible with M2C
Grid Strength	Require strong/rigid AC network. Minimum short circuit level required or critical for operation	Can operate in weak AC networks. Minimum short circuit level not required/critical for operation
Power Factor	Poor (due to reactive power demand)	Can operate at unity or controlled power factor
Efficiency	Higher (above 98%)	Slightly lower due to switching losses (95% - 98%)
Converter Size/Foot Print	Bulky due to large filters and reactive compensation	Compact due to smaller filters

Continued

Dynamic Response	Slow response due to line-commutation delay	Fast response due to self-commutation
Applications	HVDC transmission (long-distance, high power), industrial rectifiers	HVDC Light, renewable integration, DC Grids, FACTS (Flexible AC Transmission Systems)

VSC technology is better suited for deployment in Multi-Terminal HVDC (MTDC) Transmission systems because of its control benefits and consistent DC voltage. Unlike LCC technology, which has limited suitability for multi-terminal DC grids, altering the direction of power flow at any connected station would require changing the voltage polarity at all other linked DC stations. This limitation significantly reduces their operational flexibility in such systems [42]. Consequently, the use of LCC technology in MTDC deployment is primarily limited to hybrid applications that seek to make it easier to integrate sizable LCC assets into DC grids that rely on VSC.

On the other hand, traditional VSC stations are 40% - 50% smaller in terms of their physical footprint than an LCC stations with the same rating making it more and more preferable. The entire MTDC system requires a single DC voltage. In multi-vendor or multi-terminal setups, a common voltage standard simplifies integration and reduces compatibility issues [9].

4. Main HVDC Associated Equipment

HVDC systems at different DC voltage levels and capacities have different configurations and equipment. For instance, cables are used for subsea power transmission, while overhead lines are used for long-distance bulk power transmission. The equipment selection for HVDC systems is contingent upon the application scenario, function requirements, performance and as well as budget. **Figure 11** below shows the HVDC components. Most of these components are common for both LCC and VSC technology, especially the AC equipment.

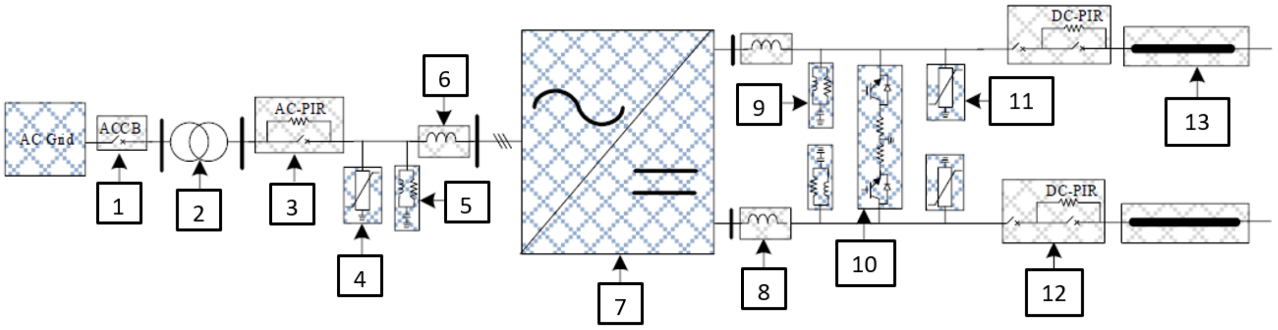

Figure 11. HVDC components [43].

4.1. The HVDC Components in Figure 11 above Are Discussed below

4.1.1. AC Circuit Breaker

The AC circuit breaker is used to connect and disconnect the HVDC system to the AC Grid, and provide safe isolation between AC and DC grid.

4.1.2. Converter Transformer

Converter Transformers provide interface between AC grid and the DC valve side of the converter. They are central to the HVDC technology as they facilitate critical voltage transformation, harmonic isolation, and impedance matching between AC networks and DC network. The converter transformer's primary role is to step up or down AC voltages to levels suitable for the converter, while providing galvanic isolation and impedance matching. In a ±100 kV DC system, for example, a 230 kV/145 kV Yg\-D transformer configuration enables effective common-mode harmonic suppression while maintaining optimal modulation indices [35] [44] [45].

4.1.3. AC Pre-Insertion Resistor

Pre-Insertion Resistors (PIRs) in HVDC systems are temporarily inserted during start-up, faults, or switching to limit inrush currents and over-voltages, protecting equipment by controlling transient surges on both AC and DC sides. PIRs are crucial during transformer energisation and HVDC link reconnection, where they mitigate high magnetization currents and capacitor charging transients, as well as during switching, by preventing sudden insulation stress and voltage dips. On the DC side, PIRs ensure controlled pre-charging of cables, lines, reactors, and capacitors in LCC and VSC-HVDC systems, thereby avoiding overcurrent tripping and enhancing voltage stability and recovery following faults, especially by reducing commutation failures in LCC applications

4.1.4. AC Surge Arrester

AC Surge Arrester protects the AC equipment's from excessive overvoltage from transients, such as switching or lightning, by dissipating the energy to the ground, thus limiting the voltage across the equipment.

4.1.5. AC Filter

The high-frequency switching of the converters produces harmonic currents. The AC filter, limit/filters harmonic currents in the network. For LCC technology, the filter also provides the additional reactive power required by the converter. The AC filter normally comprises of capacitor banks, air-core reactors and resistors. These components are designed and selected to meet the required harmonic limits in the network [43]. LCC technology generate low order harmonics (11th/13th) requiring large tuned filters. In contrast, VSC technology higher switching frequencies shift harmonics to higher order (27th/54th), permitting compact high-pass filters. VSC based Modular Multilevel Converters (M2Cs) produce very low harmonics which can be negligible.

4.1.6. AC Reactor

The AC reactor is used to limit the current rise. These reactors are air-core type, which are connected in series. For VSC technology, the AC reactor provides impedance for the converter.

4.1.7. Converter

The converter transform/converts the AC power from the grid to DC (rectifier mode) at the sending end. At the receiving end, it converts DC power back to AC (inverter mode) using semiconductor switches/valves, either Thyristor for LCC technology or IGBT for VSC technology. The detailed converter variations and operations were covered in section 3.

4.1.8. DC Reactor

The DC reactor is used to reduce maximum potential fault current, reduce the DC current ripple (smoothing current) and protecting the valves from transients from the DC network. The DC reactor is normally an air-core type, connected in series on the high voltage terminal of the converter [46].

4.1.9. DC Filter

DC filters limit/filters harmonic currents flowing in the DC network. They may be included to meet harmonic requirements depending on project scope and manufacture. The DC filters are similar to AC filters, they comprises of capacitor banks, air-core reactors and resistors [43] [46].

4.1.10. DC Chopper

DC Chopper limit DC overvoltage during faults or disturbances. In the event of a fault the excess energy within the DC network can be dissipated as heat through this DC chopper circuit. Meanwhile the pre-insertion resistors manage transient currents during start-up to protect equipment, the DC chopper circuits manage energy dissipation during abnormal operating conditions to prevent DC over-voltage and protect the system during faults or grid disturbance. Thus, the difference is “narrow and thin” because both resistors handle transient events on the DC side but differ mainly in timing and purpose: one controls over-voltage during faults (chopper resistor), the other controls inrush current during start-up (pre-insertion resistor) [47]-[49].

4.1.11. DC Surge Arrester

DC Surge Arrester protects the DC equipment’s from excessive overvoltage from transients, such as switching or lightning, by dissipating the energy to the ground, thus limiting the voltage across the equipment.

4.1.12. DC Switches Including DC PIR

DC switches are used for scheme reconfiguration, safe isolation or energising the DC network. The DC switches do not have fault interruption capability.

4.1.13. HVDC Cable or Overhead Line

HVDC cable or Overhead line transfer DC power over long distances from sending end to receiving end. In LCC system, Mass Impregnated (MI) cables are mainly used, which have higher voltage capability. In VSC technology, Cross-linked polyethylene (XLPE) or High-Performance Thermoplastic Elastomer (HPTE) cables are mainly used which have lower voltage capability. MI cable can still be used in VSC technology [43].

4.1.14. Control and Protection (Not Shown in Figure 11)

The control and protection are not shown in **Figure 11**, but they exist for the control and protection of the HVDC system. Measurement and metering devices such as current transformers, voltage transformers and Rogowski coils are installed in the HVDC system to provide measurements and monitoring for the control and protection system. The below section detail the Mach Control System which is part of control and protection.

4.2. MACH Control System in VSC HVDC

The MACH System, developed by Hitachi, serves as the intelligent control and protection platform for VSC HVDC—supporting real-time control using high-performance DSPs and FPGAs, managing pulse-width modulation in converters, rapid fault detection, advanced monitoring, IEC 61850-based communications, dynamic system response, redundancy, and cybersecurity, thereby ensuring robust, efficient, and reliable HVDC transmission [41].

4.3. MACH Control System for LCC HVDC

For LCC HVDC systems, the control system used is typically based on ABB's MACH System or similar systems developed by Siemens (SIMATIC TDC) and GE (LSM). The MACH system is common for both LCC and VSC HVDC but operates differently in each case [39]. Key control functions in LCC HVDC systems include firing angle (alpha) control to regulate DC voltage and power flow by dynamically adjusting thyristor firing angles, current control for stable power transfer, and extinction angle (gamma) control on the inverter side to ensure reliable commutation and prevent failures. **Table 4** below illustrates most common equipment in both LCC-HVDC and VSC HVDC based systems.

Table 4. Main equipment overview: LCC-HVDC vs VSC-HVDC.

Equipment/function	LCC-HVDC ±1100 kV	VSC-HVDC ±800 kV
Smoothing Components	Smoothing reactors/series (DC side current source)	Smoothing DC capacitors (DC side voltage source)
Switches	Transfer, Thyristor (SCR)-based, High speed (HSS), Bypass	Transfer, IGBT-based, High speed (HSS), Bypass
Filters and Reactors	Large AC & DC filters, AC & DC reactors	Smaller AC & DC filters (PWM control), AC & DC reactors
Transformers	Voltage & Current, phase-shifted oil-filled converter	Voltage & Current, oil-filled no phase shifting
Insulation & Bushings	Present	Present
Cooling System	Present	Present
Grounding	Electrodes for ground return, Neutral bus switch (NBS), Neutral bus grounding switch (NBGS)	Same as LCC, plus no reactive power compensation.
Surge Protection	Surge Arresters	Surge Arresters
Cables	Mass-impregnated (MI) cable	XLPE, HPTE, or MI cables
Protection & Control	MACH system panels	MACH system panels
DC Equipment	DC Cable discharge resistors, DC Chopper circuit (rare)	DC Cable discharge resistors, DC Chopper circuit

Continued

Additional Components	Reactive power compensation required	No reactive power compensation
Measurement	DC high voltage dividers for measurement	DC high voltage dividers for measurement

5. Contemporary Issues Linked with HVDC Grids

The development and implementation of HVDC grids in modern transmission systems bring numerous advantages, such as efficient long-distance power transfer and renewable energy integration. However, several contemporary challenges must be addressed to ensure their successful deployment. Below are the key difficulties associated with upcoming DC grids.

5.1. Fault Management and Complex Protection

Fault management and protection in HVDC systems are critical due to the need for extremely rapid fault detection and clearing, often within milliseconds, to maintain system stability and protect sensitive power electronic components like converter valves. Faults cause sharp voltage drops and high current surges, which the system must handle without damaging equipment, while selective fault isolation remains challenging, especially in multi-terminal HVDC grids where fault location is complicated by low impedance and the lack of zero crossing in DC fault currents. The DC fault current has no zero crossings, *i.e.* absence of natural current zero, making it difficult for the circuit breakers to extinguish arcs and interrupt faults, which rely on current zero crossing to operate effectively as compared to conventional AC system. Advanced protection algorithms and HVDC circuit breakers are being developed to overcome these challenges, but high DC fault current levels from associated capacitances make early fault interruption difficult [50].

5.2. Integration with Renewable Energy

Integration of renewable energy sources like wind and solar into HVDC systems presents challenges primarily due to their intermittent and variable nature, which complicates maintaining grid stability and balancing power flows in DC networks. Another issue is curtailment, where renewable generation must be reduced when DC lines or zones are overloaded or disconnected, limiting efficiency and economic benefits

5.3. Supply Chain Constraints

Supply chain constraints in HVDC systems are significant, driven mainly by shortages of specialized materials like high-voltage cables, DC converters, and advanced insulation, which have led to increased costs and longer lead times, sometimes exceeding 24 months for key equipment. Manufacturing bottlenecks occur due to the technical complexity of custom HVDC components and the limited production capacity concentrated among a few global suppliers, creating project timeline vulnerabilities and challenging scalability.

Original equipment manufacturers (OEMs) are moving to modular converters, e.g., VSC Modular Multilevel Converters (M2Cs) to address some of the supply chain constraints. Cable manufacturers are adopting and standardising the XLPE insulated cables, which are more environmentally friendly, reliable and have a short lead time as compared to Mass Impregnated (MI) cables. Recently, the industry is promoting a multi-vendor approach for HVDC converters in multi-terminal projects

5.4. Grid Stability and Resonance Issues

Grid stability in HVDC systems is challenged by resonance issues arising from interactions between converters especially Modular Multilevel Converters and HVDC cable/grid resonances, which can induce high-frequency oscillations and harmonic instabilities that risk system voltage instability. Weak AC grid connections in LCC HVDC systems, characterized by low short-circuit levels, worsen reliability by reducing fault current capacity, which can further destabilize the system.

5.5. Infrastructure Challenges

Capacity Limitations: Existing grid infrastructure often struggles to handle the high power transfer capabilities of HVDC systems, leading to bottlenecks and congestion.

Voltage Constraints: Maintaining stable voltage levels across DC grids is critical but challenging due to load variations, reactive power management issues, and aging equipment.

5.6. Cost Implications or High Initial Investment

High Initial Investment: Building HVDC infrastructure involves significant costs for cables, converters, and protection equipment. Rising Component Costs: Inflation, material price volatility (e.g., copper, aluminium), and geopolitical factors have further increased costs for transmission components. Upgrading or integrating existing AC infrastructure with DC technology requires significant planning and investment.

5.7. Lack of Standardization

Lack of standardization remains a major challenge for HVDC systems, with no globally accepted standards for voltage levels, protection schemes, and interoperability among different manufacturers (OEMs). This absence complicates integration with existing AC grids and multi-vendor projects, raising risks for reliability, control, and resilience. Current grid codes are often experience-based and tailored to strong AC grids, with limited provisions for weak grid connections or evolving converter technologies, necessitating urgent development of comprehensive, adaptable HVDC standards to ensure secure and compatible operation across diverse systems and future expansions. Challenge for interregional DC grids is that different countries use varying DC voltages and transmission technologies, requiring harmonization.

5.8. Limited Expertise and Workforce

The HVDC sector faces a critical shortage of skilled engineers and technicians trained in DC system operation and maintenance, with demand outpacing supply by approximately 3:1, especially in emerging technologies like MMC converters and hybrid circuit breakers. This skills gap leads to long on-the-job training periods and operational risks due to limited availability of specialized maintenance personnel.

To address the HVDC sector's workforce and expertise gap, coordinated strategies are essential. Universities and technical institutes should integrate HVDC-specific courses and practical training. Strong industry-academia collaboration—via internships, research partnerships, and joint centres like the National HVDC Centre in Cumbernauld, near Glasgow, Scotland—will foster skill development. Targeted workshops, certifications, and knowledge transfer from experienced engineers (through structured mentoring and best practice documentation) ensure ongoing competency. Government and industry incentives, scholarships, and clear career pathways further attract talent, while global collaboration and benchmarking keep the workforce abreast of emerging best practices. These combined efforts in education, training, collaboration, and policy underpin sustainable HVDC workforce growth

To address the skills, "vacuum" problem the National HVDC Centre is running a sustained programmes of specialist training, academic engagement and industry knowledge exchange, aimed at both current practitioners and future engineers. It delivers regular "Introduction to HVDC and Project De-risking" and advanced replica/small-signal analysis courses for TOs, NESO and international TSOs, often training large cohorts in single sessions and using real-time simulation facilities to develop operator capability. The Centre acts as a national hub for knowledge dissemination through webinars, short films, quarterly newsletters, LinkedIn outreach and the annual HVDC Operators Forum, all structured to spread lessons learned from projects and innovation work across GB and overseas stakeholders. It also supports a pipeline of new HVDC specialists by collaborating with multiple universities, hosting Academic Research Days, EngD/PhD projects and student visits, and providing guest lectures that connect cutting-edge research on multi-terminal control, converter interactions and AC-DC power flow with practical system operation needs.

5.9. Interoperability with AC Systems

Hybrid AC/DC grids require advanced power electronics interfaces, and managing power flow between AC and DC sections can be complicated. Resonance and instability between AC and DC systems can lead to operational challenges.

5.10. Regulatory Hurdles and Dilemmas for Future HVDC Grids

Regulatory hurdles for future HVDC grids include complex, lengthy approval processes involving multiple permits and stakeholder consultations, which are further complicated by cross-border projects. Existing grid codes, mainly designed for traditional AC systems, lack provisions for HVDC and hybrid AC/DC grids, especially regarding weak grid connections and operational challenges like system inertia and fault ride-through, necessitating urgent updates. Revenue regulation frameworks may limit investment attractiveness and innovation due to risk aversion. Interoperability concerns arise from multi-vendor environments, raising legal challenges around competition and intellectual property. Regulators must balance fostering innovation necessary for decarbonisation with protecting consumers from costs and reliability risks, making regulatory design a delicate challenge for future HVDC deployment [51].

Addressing some of these challenges will require advancements in technology (e.g., faster circuit breakers), better integration strategies for renewables, enhanced manufacturing capacity for critical components, and robust planning for grid stability. Hitachi Energy's has developed HVDC circuit breaker which will address some of the fault Management issues. Hitachi Energy's HVDC circuit breaker technology has achieved significant milestones in high-current interruption testing and Research &Development for DC grid applications.

Hitachi Energy's hybrid design successfully interrupted 20 kA fault currents within 3 milliseconds during tests at KEMA Laboratories in Arnhem, Netherlands. The breaker generated a transient interruption voltage (TIV) peak of 490 kV and absorbed 7 – 10 MJ of energy during suppression [52]. Tests were conducted under the EU-funded PROMOTioN project, witnessed by European TSOs and grid developers in February 2020.Demonstrated capability to handle reverse currents (16 kA at 160 kV) and continuous currents (3.3 kA at 350 kV) [50] [52].

6. Application Project Cases

6.1. The Skagerrak 4 HVDC Project

The Skagerrak 4 project is a point to point bipole HVDC transmission link connecting Kristiansand in southern Norway to Tjele on Denmark's Jutland peninsula. Skagerrak 4 utilizes Voltage Source Converter technology at both terminals, each converter station is rated for a transmission capacity of 700 MW and operates at a voltage level of ±500 kV [51]. The link spans approximate length of 244 km , comprising of 140 km of submarine cable and 104 km of land cable [53]. **Figure 12** below shows the schematic diagram of Skagerrak 4.

Skagerrak 4 operates in a bipolar configuration alongside the pre-existing Skagerrak 3 link, which uses classic Line Commutated Converter technology. This integration is notable as it was the first of its kind combining VSC and LCC technologies in such a configuration. Skagerrak 3 is an HVDC link with LCC stations at both ends which are rated for a transmission capacity of 440 MW at a voltage level of ±350 kV [37]. It's worth noting that some sources report a transmission capacity of 500 MW for Skagerrak 3. This discrepancy may be due to differences in reporting standards or upgrades over time.

Skagerrak project consists of 4 HVDC converters as shown in **Figure 12** below.

Skagerrak 1 & 2 is a bipole LCC link rated at 500 MW with a voltage of ±250 kV. Skagerrak 3 & 4 is a hybrid (LCC & VSC) bipole system with a capacity of 1200 MW (500 MW for Skagerrak 3 & 700 MW for Skagerrak 4) with different voltage levels.

- Bipolar Operation with Different Voltage Levels.

In the Skagerrak 3 & 4 system, the two poles operate at different voltages (350 kV vs 500 kV), so a balanced current return path is needed. To ensure stable operation, a controlled return path using a Neutral Bus System that dynamically manages current flow between the two systems is used at the converter stations. The neutral points of both Skagerrak 3 and Skagerrak 4 are connected at each terminal (Kristiansand and Tjele) to allow current imbalances to be managed effectively.

- Grounding and a Dedicated Metallic Return Path.

Since Skagerrak 4 operates at a higher voltage, its current is lower than that of Skagerrak 3 for the same power level. The difference in current is returned via a dedicated metallic return (DMR) conductor instead of the ground and this ensures proper balancing of the system while minimizing ground current effects.

Skagerrak 3:

DMR Rating: The DMR is designed to handle the full rated current corresponding to the 500 MW transmission capacity.

The current rating can be calculated by: Current = $\frac{\text{Power}}{\text{Voltage}} = \frac{500\,\text{MW}}{350\,\text{kV}} \approx 1.43\,\text{kA}$.

Therefore, the DMR is rated to carry approximately 1430 amperes (A).

Skagerrak 4:

DMR Rating: Similarly, the DMR is rated to handle the full current associated with the 700 DMR Rating:. Using the same formula: Current = $\frac{\text{Power}}{\text{Voltage}} = \frac{700\,\text{MW}}{500\,\text{kV}} \approx 1.4\ \text{kA}$.

Thus, the DMR is rated for 1400 A.

- Power Reversals Handling.

Skagerrak 3 (SK3) uses a Line-Commutated Converter, which requires voltage polarity reversal for power reversal and Skagerrak 4 (SK4) uses a Voltage-Source Converter, which can reverse power flow without changing voltage polarity, The MACH control system handles these differences, ensuring that both links operate efficiently in a coordinated manner. The SK4 pole's VSC is fully insulated in both positive and negative voltage polarities, and changeover switches are positioned in the DC yard to work with the SK3 pole to achieve power flow reversal and eliminate ground current during bipolar operation [37]. Even though Skagerrak 3 and Skagerrak 4 operate at different voltage levels (±350 kV and ±500 kV), they are synchronized using a common neutral bus and a controlled return path. In the Skagerrak system, the negative pole of Skagerrak 4 (−500 kV) effectively serves as the Dedicated Metallic Return (DMR) for Skagerrak 3 (±350 kV) under normal bipolar operation.

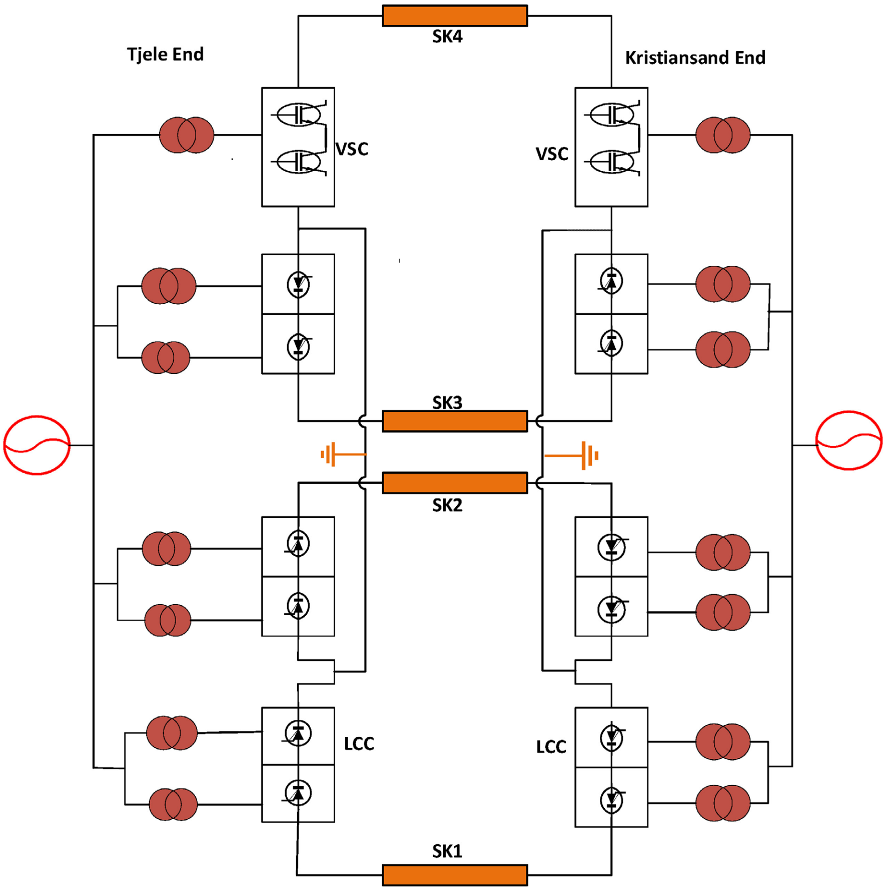

Figure 12. Schematic diagram of single line diagram of Skagerrak 4 HVDC.

6.2. NordLink HVDC Project

NordLink is a point-to-point rigid bipole HVDC interconnector linking the power grids of Norway and Germany. The converter stations are situated near Tonstad in southern Norway and Wilster in northern Germany. The link efficiently manages the bidirectional flow of renewable energy between the two countries. It utilizes Voltage Source Converter technology, operating at ±525 kV with a transmission capacity of 1400 MW (each station is rated at 1400 MW). The link spans a total length of 623 km, comprising 516 km of submarine cable, 54 km of land cable in Germany, and 53 km of overhead line in Norway [18] [54] [55].

With this rigid bipole design, if one cable fails, the whole system shuts down as it lacks flexibility as with a normal flexible bipole design which can operate independently and perhaps allowing one pole to run temporarily in monopolar mode with a ground return [52]. Figure 13 shows the layout of the Nordlink project.

6.3. Greenlink HVDC Project

Greenlink is a point-to-point symmetrical monopole HVDC interconnector that links Pembrokeshire, Great Britain, with Wexford, Republic of Ireland. January 2025 was the announced date of its commercial operation. Voltage Source Converter technology is used in the project to enable the asynchronous link between

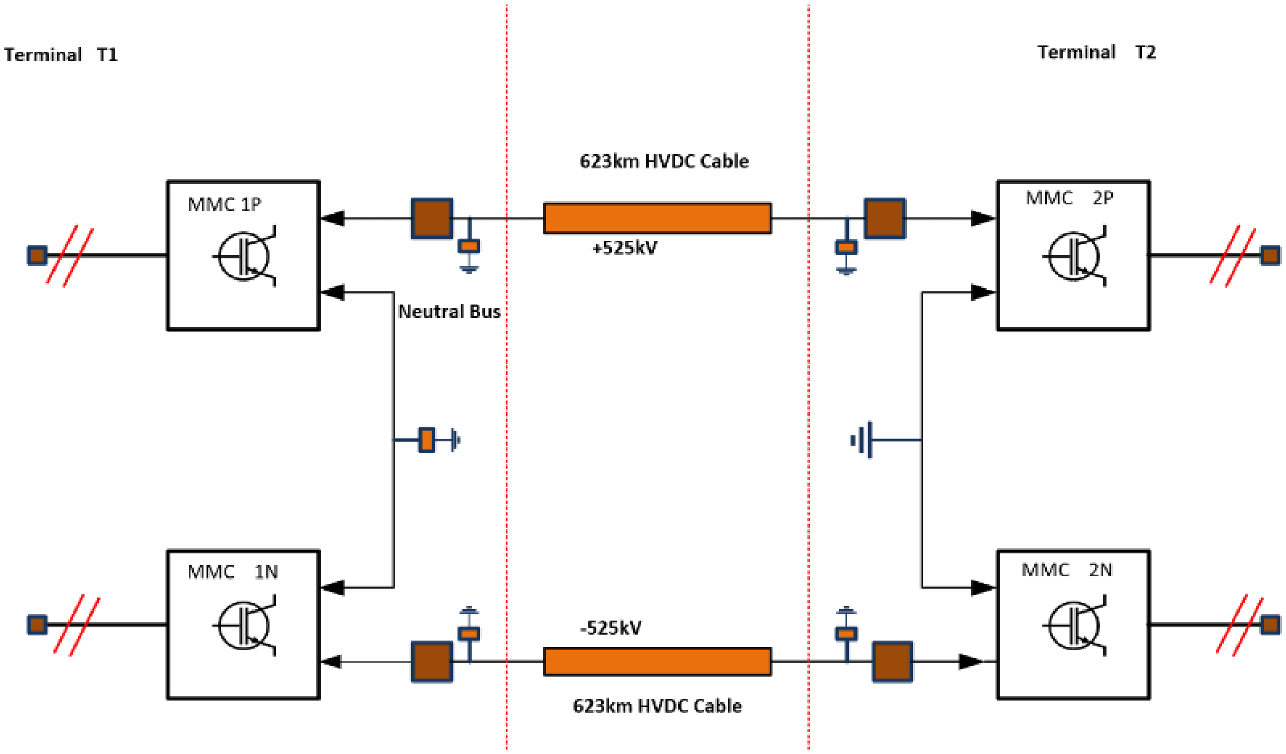

Figure 13. Layout for Nordlink rigid bipolar VSC HVDC technology.

the transmission networks, operating at ±320 kV with a transmission capacity of 504 MW. The interconnector spans a total length of 190 km, comprising of 160 km of submarine cable, 30 km of land cable [56].

Bidirectional power transfer is made possible via the interconnector, contingent on market circumstances. The symmetrical monopole design of the Greenlink HVDC converter system, which uses half-bridge topology, is depicted in Figure 14 below. The IGBT-based half-bridge converter modules have a 4.5 kV voltage and a DC current capability of over 2 kA, which is consistent with the latest advancements in XLPE technology.

In general, symmetric monopole designs require less land and are easier to build and maintain than other layouts. The link can transmit power at ±504 MW (measured at import) and contribute ±166 MVar in reactive power when operating in normal mode.

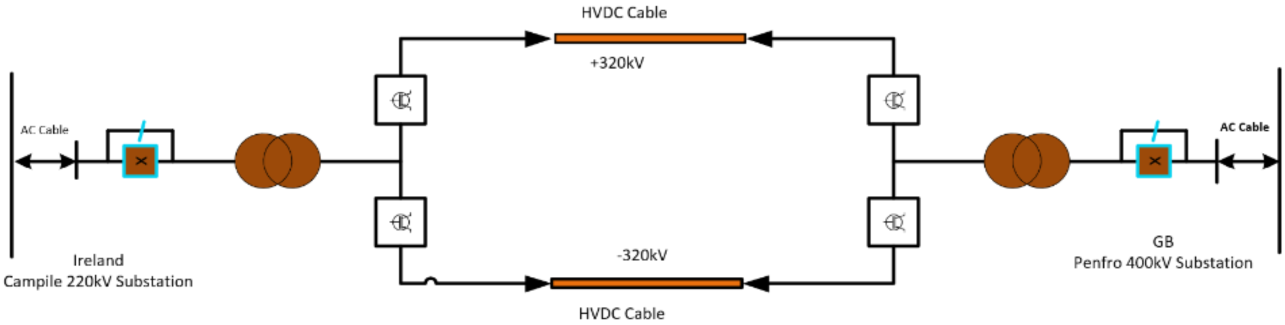

Figure 14. Symmetrical monopole design for greenlink HVDC interconnector.

Each of the six converter modules that make up the converter at both locations is composed of series-connected submodules with a power supply and a capacitor [57].

Although certain 320 kV XLPE HVDC cable systems can function with a maximum power flow of roughly 1000 MW [16], the Greenlink interconnector's capacity is only 504 MW, mainly because of the maximum permitted infeed on the Irish power system at the time of establishing a grid connection (2019). The maximum permitted infeed/outfeed capacity will rise to 700 MW by 2030 [56].

6.4. Caithness-Moray-Shetland Multi-Terminal HVDC Project

Caithness-Moray-Shetland is a three terminal symmetrical monopole HVDC link in northern Scotland. It utilises Voltage Source Converter technology with Modular Multilevel Converter (M2C) stations at Spittal in Caithness; Blackhillock Substation in Moray; and Upper Kergord in Shetland. This link provided first time connection of Shetland to the Great Britain (GB) transmission network for the first time and enables the connection of renewable generation located in Shetland.

The link operates at ±320 kV with a transmission capacity to carry up to 1200 MW. The Shetland station has a power rating of 600 MW; the Spittal and Blackhillock converters are rated at 800 MW and 1200 MW respectively. This is the first multi-terminal HVDC interconnection in Europe driven by the Voltage Source Converter technology [9] [24] [58] [59]. This energy "artery" will facilitate the UK's energy transformation by providing a transmission link for the much-needed clean renewable power to Scotland, enabling the harnessing and development of the Shetland wind power resources.

On completion of the Gremista 132kV grid supply point the HVDC link will contributes to the security of Shetland's electricity supply and reduce the dependence on fossil fuels. Scottish Southern Electricity Networks (SSEN) can effectively

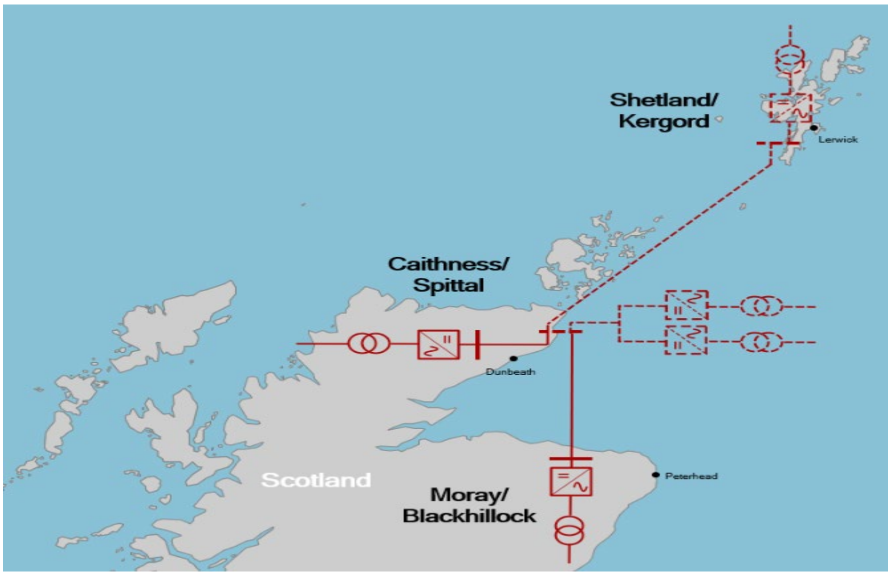

Figure 15. The caithness-moray HVDC link in northern Scotland (solid), including shetland link which is now complete and possible future offshore connections (dashed) [60].

combine wind and hydro power to meet user needs while also increasing the reliability and capacity of the power grids in Scotland and on Shetland by utilizing Hitachi Energy's Voltage Source Converter technology, marketed as the HVDC Light, which has high controllability and flexibility. The technical solution has a minimal environmental footprint because of its optimized design and low losses. **Figure 15** shows the schematic layout of the Caithness-Moray HVDC link.

6.5. The Wudongde Multi-Terminal HVDC Project

Wudongde is a three-terminal bipole Ultra High Voltage Direct Current (UHVDC) grid. The system combines LCC technology at the Kunbei station in Yunnan and VSC technology at the Liubei and Longmen stations in Guangxi and Guangdong provinces, respectively. This hybrid approach optimizes efficiency and flexibility while addressing challenges like reactive power control [61]. The link operates at a voltage of ±800 kV, with a transmission capacity to carry up to 8 000 MW. The project is designed to transmit hydropower from the Wudongde Hydropower Station in Yunnan Province to Guangxi and Guangdong provinces [62]. **Figure 16** shows the layout diagram of Wudongde project.

Table 5. Converter stations parameters.

Parameter	Kunbei Station	Liubei Station	Longmen Station
Converter technology	LCC—each pole consists of two 12-pulse in series	VSC—use M2Cs with mixed half-bridge/full-bridge submodules.	VSC—use M2Cs with mixed half-bridge/full-bridge submodules.
Voltage (kV)	800	800	800
Capacity (MW)	8000	3000	5000
Converter Transformer Capacity (MVA)	1217	870	1440

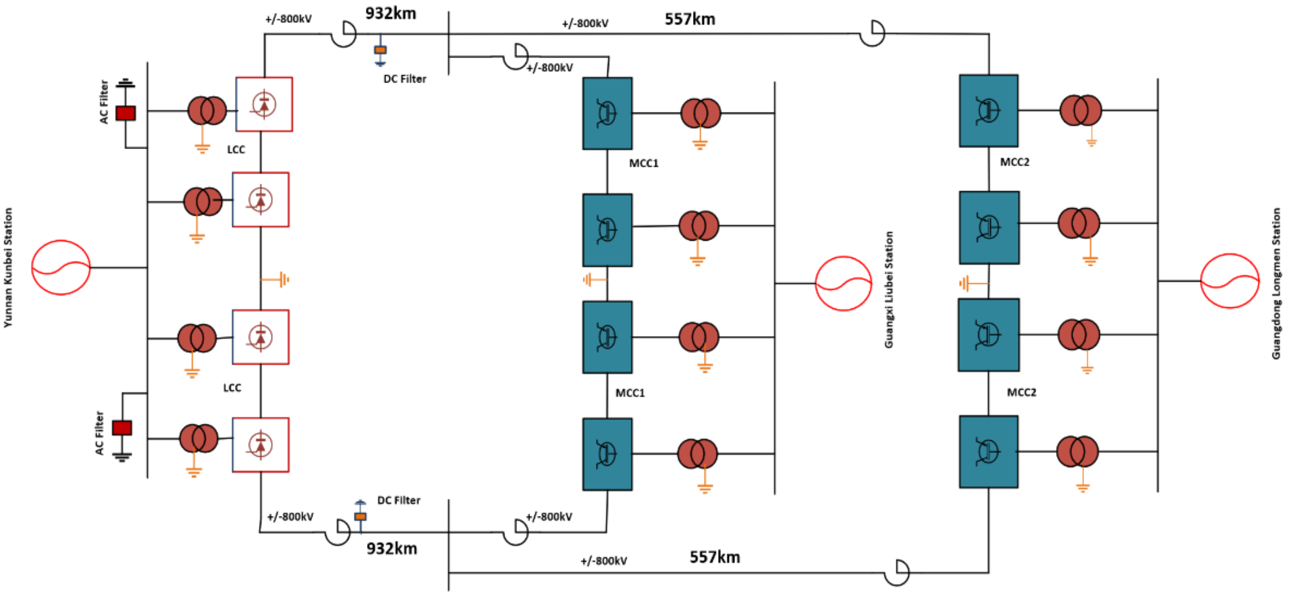

Figure 16. Layout diagram of Wudongde UHVDC transmission project.

The converter stations parameters at the three stations are shown in Table 5 below [63].

Transmission Line:

- Kunbei Converter Station (Yunnan) to Liubei Converter Station (Guangxi). approximately 932 km OHL.
- Kunbei Converter Station (Yunnan) to Longmen Converter Station (Guangdong) approximately 1489 km OHL

6.6. The Zhangbei Multi-Terminal HVDC Project

Zhangbei is a four-terminal bipole HVDC link that integrates renewable energy, *i.e.* wind, solar, and pumped hydro, to load centres. It connects wind power in Zhangbei station, Kangbao station which integrates with photovoltaic power to Beijing's load centre, with FengNing station integrating pumped storage serving as a hub for balancing power fluctuations and the Changping station which serves demand. The link uses VSC technology, operating at a voltage of ±500 kV, with a transmission capacity of 3000 MW. The Changping station has a power rating of 3000 MW; and the rest of the stations are all 1500 MW [64]. The four station are all connected and supported by a 500 kV AC grid.

Figure 17 shows the layout of Zhangbei VSC-MTDC project.

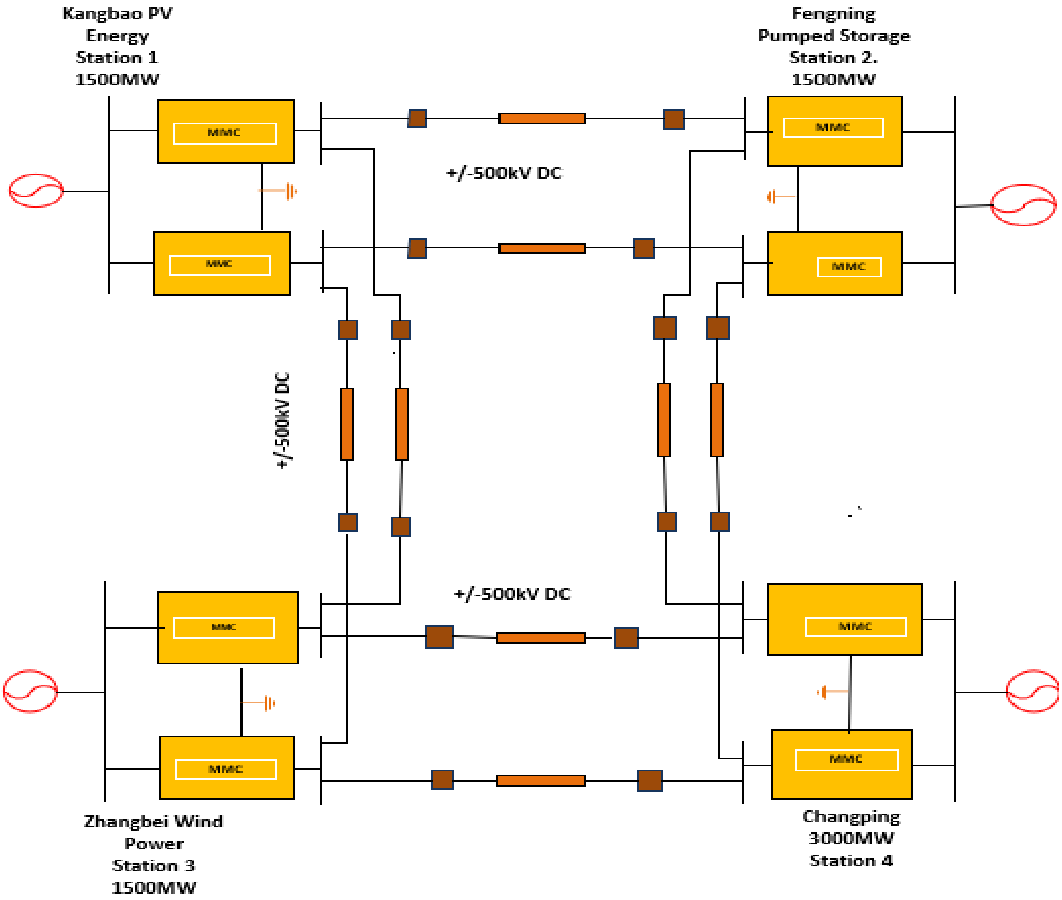

Figure 17. Configuration and layout of Zhangbei VSC-MTDC grid.

This project is a blueprint for larger DC grids, with plans to expand connectivity and capacity for broader renewable integration in Northern China. The Zhangbei VSC-MTDC grid exemplifies cutting-edge HVDC technology, combining scalability, fault resilience, and renewable energy optimization to address modern power grid challenges.

7. Conclusion

This review paper offers a comprehensive examination of High Voltage Direct Current (HVDC) systems, covering both established and emerging technologies through analysis of real-world projects and literature. It provides a detailed comparison of HVDC converter types, highlighting their performance and suitability for different applications. The paper emphasizes the growing role of multi-terminal HVDC systems and DC grids in modernizing power transmission and integrating renewable energy. It also discusses current challenges in deployment, including technical, operational, and regulatory issues, underscoring the importance of continued research and innovation. Overall, the review aims to inform future research and guide practical implementation, helping power engineers understand HVDC's integration with AC networks and its potential in next-generation power systems.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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