

Review

Overview and Assessment of HVDC Current Applications and Future Trends

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Abstract: High voltage direct current (HVDC) technology has begun to gather a high degree of interest in the last few decades, showing a fast evolution of achievable voltage levels, transfer capacities, and transmission lengths. All these changes occurred in a context in which power system applications are highly dependent on HVDC technologies such as energy generation from renewable sources (e.g., energy generated in offshore wind power plants), power exchanges between asynchronous networks, submarine cables, and long-length transmission overhead lines have become more common worldwide. This paper tries to summarize the current state of HVDC technologies, both voltage-source converters and current-source converters, the main components of converter substations, control strategies, key challenges arising from their use, as well as the future prospects and trends of HVDC applications. This paper represents the first step in setting the background information for analyzing the impact of a VSC-HVDC connection on the stability of the Romanian transmission network during steady-state and dynamic operation.

Keywords: applications of HVDC transmission systems; control strategies; technology



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1. Introduction

The electrical industry is marked by a great “battle” between direct current (DC) and alternating current (AC) solutions. With the increase in energy demand, and therefore in energy generation, more and more matters have been registering to the use of AC solutions. For example, there are great difficulties in increasing the voltage level of submarine cables (and therefore their ability to transfer high power).

Also, the existence of high generation capacity hydroelectric projects under development in areas of exploitation remote from consumption has become a problem for the classical application of power transmission by using alternating current (transmission of energy at AC over long distances raises issues in terms of static stability and increases total power losses) [1].

At the current moment, the following are the two main high voltage direct current (HVDC) technologies: line-commutated converters (LCC), also known as current-source converters (CSC) using thyristors, and voltage-source converters (VSC)-HVDC, using IGBT transistors, both are suitable for a wide range of applications [1].

For long-distance and high-capacity transmission links, CSC-HVDC technology has both higher efficiency and a higher power transfer capacity than classical AC solutions.

In the case of power transmission from offshore power plants or from other remote areas with limited space, VSC-HVDC is the preferable technology, bringing great active and reactive power control capabilities.

The modern form of HVDC systems uses technologies developed extensively in the 1930s (mercury-arc valves) in Sweden and Germany. Prior commercial applications included an HVDC system in the Soviet Union in 1951 between Moscow and Kashira and a 100 kV, 20 MW link between the island of Gotland and mainland Sweden in 1954 [1].

Thyristor valves have been used for the first time in HVDC applications since the 1970s. Many of the limitations of mercury-arc technology have been removed. The first LCC-HVDC commissioned was the Eel River Converter Station in Canada, in 1972 [2].

An improved solution to the thyristor valves were the IGBT valves used in voltage source converters. In 1999 ABB commissioned the first commercial VSC-HVDC connection between the islands of Gotland and continental Sweden, consisting of submarine cables with a rated capacity of 50 MW, and a rated voltage of ± 80 kV [3,4].

Figure 1 shows the evolution of power electronics, from mercury-arc to IGBT transistors, in parallel with HVDC converter development [5].

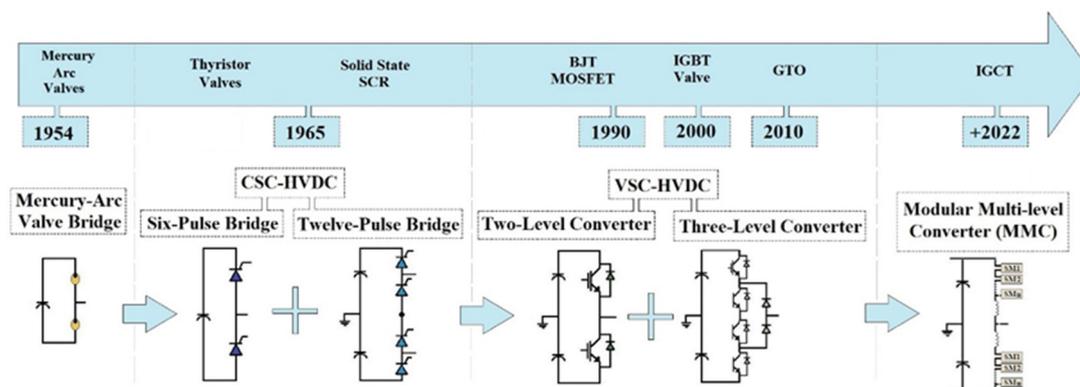


Figure 1. HVDC technological evolution.

HVDC technology has a bright future. Several new technologies are rapidly developing (e.g., modular multilevel converters—MMC, cascaded two-level converters—CTL, hybrid VSC-CSC links) in order to meet the increasing requirements of modern power systems.

The objective of this contribution is to provide a qualitative overview and assessment of current applications and future trends in HVDC. In order to classify the key publications, the databases have been explored, articles from journals and conference proceedings have been analyzed, by applying questions, metadata, titles, abstracts, and keywords. With the focus of better understanding the most effective strategies to implement HVDC technologies in power transmission systems, different concepts, advantages, and barriers are investigated together with a qualitative analysis of the most innovative and interesting technical solutions.

The methodology of our contribution has followed four main steps, and the results have been clustered into the following categories: (1) an updated qualitative overview of the current state of HVDC technology (considering the most recent developments for the identified five main areas of applications and four common types of HVDC link topology); (2) an overview of the theoretical background on the main components of HVDC converter substation, methods, and control strategies; (3) an overview of key challenges arising from the use of HVDC technology and the following several issues that need to be addressed properly: DC circuit breaker solutions, reliability and maintenance of HVDC conversion substations, and multi-terminal HVDC system operation; (4) a qualitative overview of some of the most successful trends and future applications of HVDC transmission systems and a personal perspective on future developments of HVDC technologies.

In the rest of the paper, the abbreviations and terms presented in Table 1 will be used.

Table 1. A list of abbreviations and terms used in the paper.

Term	Meaning
HVDC	High-Voltage Direct Current
DC	Direct Current
AC	Alternative Current
LCC (CSC)	Line-Commutated Converter (Current-Source Converter)
VSC	Voltage-Source Converter
MMC	Modular Multi-Level Converter
CTL	Cascaded Two-Level Converter
GW	Gigawatt
IGBT	Insulated Gate Bipolar Transistor
BJT	Bipolar Junction Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
GTO	Gate Turn-Off Thyristor
IGCT	Integrated Gate Commutated Thyristor
OHL	Overhead Line
B2B	Back-to-Back
CB	Circuit Breaker
SSCB	Solid-State Circuit Breakers
SCC	Short Circuit Current
UFD	Ultra-Fast Disconnecter
LCS	Load Commutation Switch
FEU	Forced Energy Utilization
FACTS	Flexible Alternating Current Transmission System
MTDC	Multi-Terminal DC Links
PLL	Phase-Locked Loop
RPV	Reactive Power Control Loop
AVC	Active Voltage Control Loop
APC	Active Power Control Loop
CCR	Constant Current Characteristic Rectifier
CCI	Constant Current Characteristic Inverter
CIA	Constant Ignition Angle (α)
CEA	Constant Extinction Angle (γ)
UGC	Underground Cables
XLPE	Cross-Linked Polyethylene Cable
CB	Circuit Breaker
SM	Submodule

2. Main Areas of HVDC Applications

HVDC technology has gradually gained worldwide popularity. The use of DC links, to the detriment of AC classical solutions, is justified by several advantages (e.g., active power control, higher transfer capacities, no reactive power, longer transmission possible lengths, and lower active power losses) in some cases being the only feasible technology [6,7].

The main areas of HVDC applications include:

- Long-distance power transmission lines;
- Submarine cable transmission (connections with lengths greater than 50 km usually used for offshore wind power plants power evacuation);
- Interconnection of systems that operate asynchronously;
- Multi-terminal HVDC systems.

- **Long-distance bulk power transmission**

In some cases, when high powers (of the order of GWs) have to be carried over long lengths (lengths that exceed the critical distance, which at the moment is in the order of hundreds of kilometers) HVDC transmission systems represent a cheaper and more efficient alternative in terms of investment costs and power losses to classical AC technologies [8,9].

At the current moment, the longest HVDC transmission overhead line and the highest transfer capacity link is the “Changji-Guquan Link” (CSC–HVDC) from China [10], with a total transfer capacity of 12 GW (1100 kV) and a total length of 3324 km. Figure 2

shows the advantages of HVDC technologies used for long-distance links in terms of total investment costs.

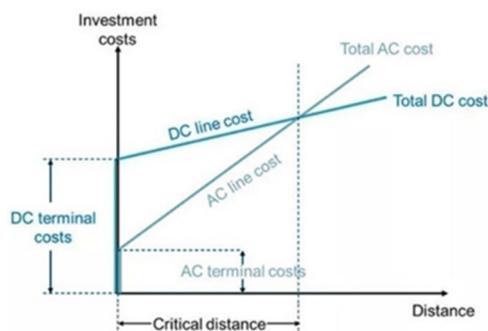


Figure 2. HVDC technology—Economical advantage.

- **Submarine Cable Transmission**

HVDC technology is suitable for transporting power through submarine cables, mostly when the distance is greater than 50 km. The HVDC cables do not have the main physical restrictions of classical AC cables, which due to the reactive power component and the capacitive currents have a lowered total active power transfer capacity [11]. Although the reactive component can be compensated by using shunt reactors, this is difficult to implement for submarine cables.

In the case of submarine interconnections between networks operating asynchronously or offshore wind power generation transmission from remote places, the preferred solution is using VSC-HVDC technology, which brings several advantages, such as low space requirements and highly flexible active and reactive power control capabilities [12]. The longest up-to-date power transmission HVDC submarine cable is associated with the “NorNed Link” [13], between Norway and Netherlands, with a total length of 580 km and a total transfer capacity of 700 MW.

- **Asynchronous Ties**

Interconnections between networks that operate asynchronously can be made by using HVDC technologies.

The main purposes of these links are the following: to improve safety in operation (power exchange through the interconnection can be precisely controlled, improving system stability), to provide additional active power reserves and emergency assistance for neighboring systems, and to satisfy other economic aspects (power exchange contracts) [14,15].

Most of the time, asynchronous ties use the HVDC back-to-back (B2B) configuration topology, which doesn’t require a transmission cable or overhead line, thus reducing the total cost of the link. Another advantage of back-to-back connections is that they do not propagate failures from one network to another (for example, a cascading blackout phenomenon) [14,15].

The “Gaoling B2B Interconnection”, connecting the 500 kV North China and Northeast China grids [16], is the back-to-back converter interconnection with the largest capacity in the world. Phase I, commissioned in 2008, of the project consists of a bipolar ± 500 kV, 1500 MW link.

- **Offshore Wind Power Plant Transmission**

For transporting the energy produced in the offshore wind power plants located in remote areas away from the mainland, the most suitable HVDC-type technology is represented by VSC-HVDC.

The independent control capabilities of both active and reactive power flow, the ability of “black-start”, as well as low ground footprint allow VSC-HVDC technology to operate in isolated environments, such as on offshore platforms [17,18].

At the moment, the most representative offshore wind power plants' transmission HVDC links are located in the North Sea [19,20] (having the main purpose of injecting energy into the German Power System):

- *DolWin 1* (2015—800 MW), *DolWin 2* (2015—900 MW), *DolWin 3* (2018—900 MW);
- *BorWin 1* (2009—400 MW), *BorWin 2* (2015—800 MW), *BorWin 3* (2019—900 MW);
- *HelWin 1* (2015—576 MW), *HelWin 2* (2015—690 MW);
- *SylWin 1* (2015—864 MW).

- **Multi-Terminal HVDC Systems**

Given the advantages brought by the current two-terminal HVDC connections in carrying a large amount of power whilst providing advanced power flow control capabilities, it is necessary, especially in the context of the increasing number of interconnected power systems and offshore wind power plants, to develop MTDC systems (multi-terminal-DC systems) [21].

Within an MTDC connection, the HVDC converters can be operated by turn either as an inverter or as a rectifier, thus being able to control the power flow inside the DC network [22].

At the current moment, some of the most important MTDC interconnections worldwide are represented by the following:

- *MTDC Italy–Corsica–Sardinia* (SACOI–CSC–HVDC–1992)—three terminals (200/50/200MW);
- *MTDC Quebec–New England* (1992—CSC–HVDC)—five terminals (2250/2139/690/1800MW);
- *MTDC Nanao* (China, 2013—VSC–HVDC)—three terminals (200/100/50MW);
- *MTDC Zhoushan* (China, 2014—VSC–HVDC)—five terminals (400/300/100/100/100 MW).

3. Types of HVDC Links Topology

For connecting two networks or systems, various types of HVDC links are used. Usually, HVDC topologies are classified into the following main four types.

3.1. Monopolar Links

Monopolar links, Figure 3, are most suitable in the case of power transmission over long distances, especially in the particular case of long submarine cables. An HVDC monopolar link with a ground return conductor represents the most feasible solution in terms of cost reduction. In some cases, there are infrastructure or environmental restrictions preventing the use of a ground return. In these cases, it is necessary to adopt a dedicated metallic return conductor, resulting in increased costs and losses [23,24].

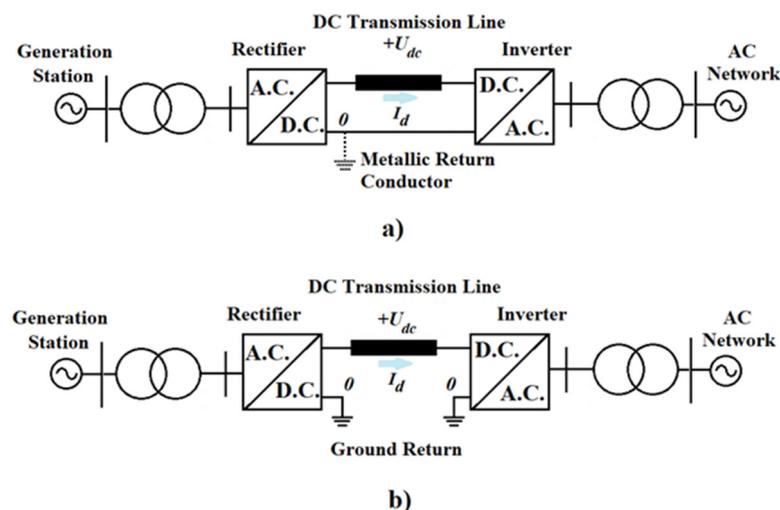


Figure 3. HVDC monopolar links: (a) metallic return conductor, (b) ground return.

3.2. Bipolar Links

A bipolar link is a mix of two independent monopoles. The most important aspect of bipolar normal operation is that, through the return conductor, there is an imbalance current as small as possible. This type of configuration applies in cases where the transfer capacity of a monopolar connection is insufficient, as well as in cases where it is desired to increase power supply security [25,26].

In the event of a fault at the level of one of the poles, or in the case of maintenance work, the other pole can carry up to 50% of the total transfer capacity of the bipolar link. Another advantage of a bipolar connection compared to the alternative solution of using two independent monopolar connections is the lower loss level (the existence of a single return conductor).

- **Bipolar Link with Ground Return Path**

This type of connection, Figure 4, is commonly used for bipolar links, with a number of advantages, such as a high degree of flexibility in operation in cases of low transfer capacity available during network contingencies or maintenance work. In the case of a fault on a single pole, the power flow associated with the unaffected pole is taken over by the return ground path, the defective pole being isolated [25,26].

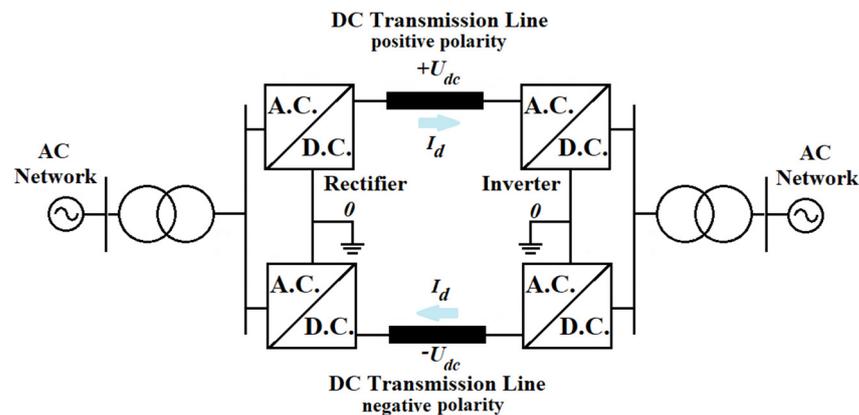


Figure 4. HVDC bipolar links ground return.

- **Bipolar Link with Dedicated Metallic Return Path**

If there are permanent or temporary restrictions on the use of electrodes for creating the ground return path, or if the transmission distance is relatively short, a dedicated metallic return conductor, Figure 5, can be used in order to achieve a return path [25,26].

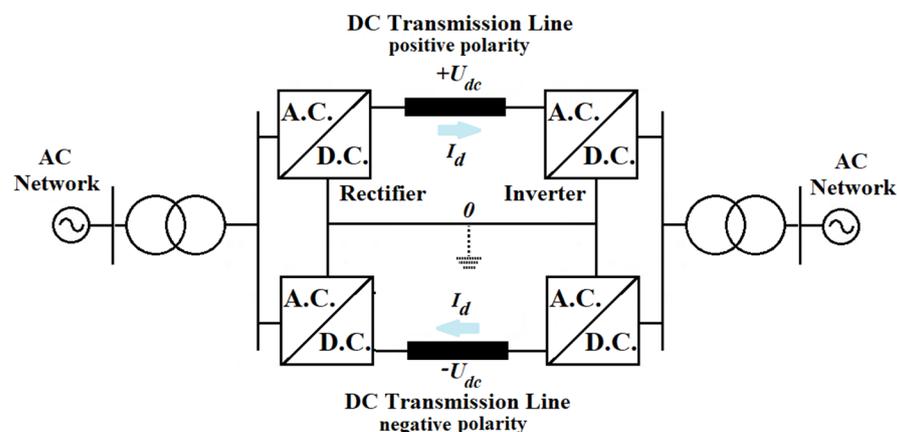


Figure 5. HVDC bipolar links metallic return conductor.

3.3. Back-to-Back Links

“Back-to-Back” (B2B) links, Figure 6, are characterized by the fact that both the inverter and the rectifier are located in the same building. These types of links are mainly used for the interconnection of two AC networks that operate asynchronously or at different frequencies. Also, “back-to-back” links can be used inside a network in order to control the power flow between different areas of it [27,28].

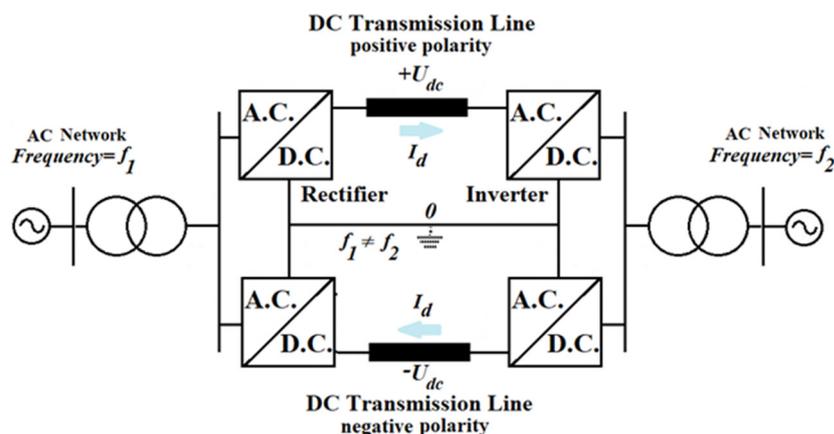


Figure 6. HVDC back-to-back links.

3.4. Homopolar Links

Homopolar links, Figure 7, are similar to bipolar links, but compared to the former, both independent poles have the same polarity (usually negative) and always work using a metal or ground return conductor. Additionally, in the case of homopolar links, the poles work independently in parallel, thus reducing the costs associated with insulation [29].

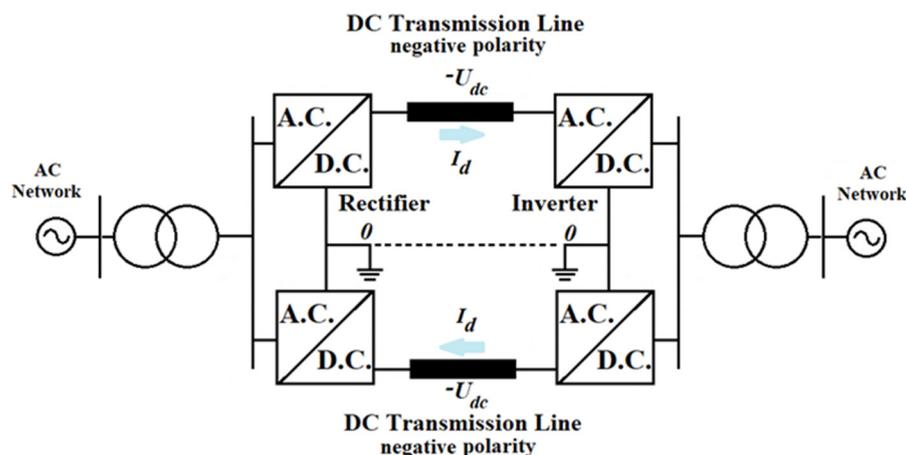


Figure 7. HVDC homopolar link.

4. Main Components of HVDC Substations and Control Strategies

4.1. Main Components of HVDC Converter Substations

The AC network is connected to the HVDC converter station by a converter busbar, represented by one or more typical AC busbars, to which the converter is connected. [30,31].

- The main types of equipment associated with the AC part of the converter substation include the following [31]: AC-OHL/UGC; busbar system/systems; AC switchgear (disconnectors/switches/circuit breakers); conversion power transformers; measuring instruments AC (voltage/current transformers); AC harmonic filters; AC shunt capacitors.

The DC part of the converter substation is connected to the AC part by using a converter (VSC or CSC type) located within the building/room of the converter valves.

- The main pieces of equipment associated with the DC part of the converter substation include the following [31]: DC-OHL/UGC (usually XLPE cable in case of VSC technology); DC harmonic filters; phase reactor (VSC-HVDC); DC capacitor (VSC-HVDC); smoothing reactor; measuring instruments DC (voltage/current transformers); DC switchgear (disconnecter switchers/circuit breakers);

In Figure 8, the basic structure of an HVDC substation in the case of CSC-HVDC is presented, and in Figure 9 the basic structure of VSC-HVDC is presented [31–35].

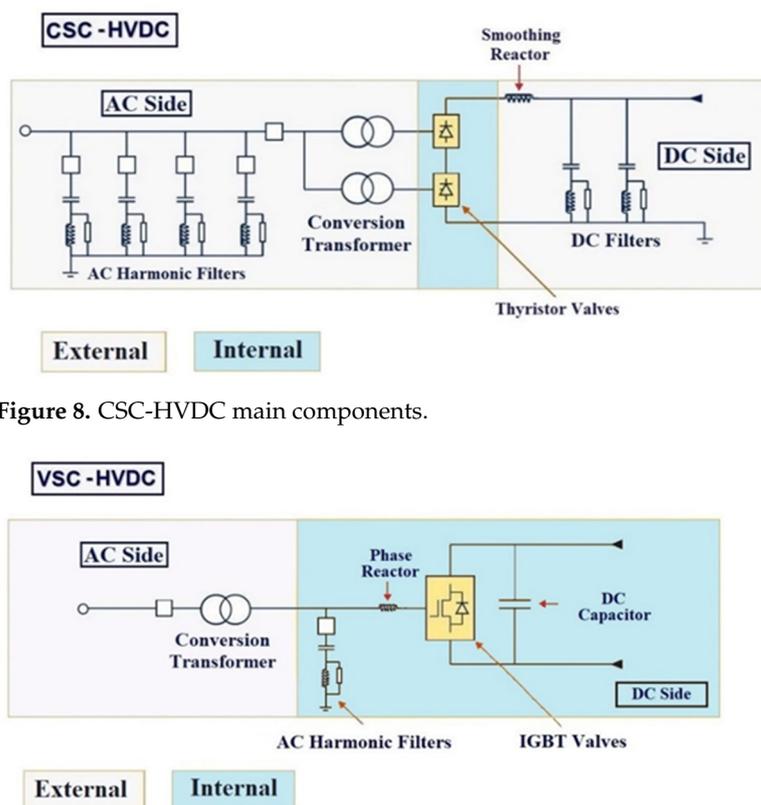


Figure 8. CSC-HVDC main components.

Figure 9. VSC-HVDC main components.

In the rest of the paper, the abbreviations and terms presented in Table 2 will be used.

Table 2. A list of symbols and terms used in the paper.

Term	Meaning
P_d	Active power on DC link
P_{dr}	Active power at the level of rectifier
P_{di}	Active power at the level of inverter
U_d	DC voltage on DC link
U_{dr}	DC voltage at the level of rectifier
U_{di}	DC voltage at the level of inverter
I_d	Current through the DC link
R_{cr}	Commutation resistance at the level of rectifier
R_{ci}	Commutation resistance at the level of inverter
R_L	Resistance of the DC link
X_{kr}	Short-circuit reactance at the level of rectifier
X_{ki}	Short-circuit reactance at the level of inverter
U_{dr}	DC voltage at the level of rectifier
U_{di}	DC voltage at the level of inverter
α	Ignition angle

Table 2. Cont.

Term	Meaning
γ	Extinction angle
I_{ref}	Reference current (DC side)
U_{ref}	Reference voltage (AC Side)
P_{ref}	Reference active power (AC Side)
Q_{ref}	Reference reactive power (AC Side)
ΔI_m	Current margin
I_{0r}	Reference current value rectifier
I_{0i}	Reference current value inverter
P	Active power at the AC side of HVDC Link
Q	Reactive power at the AC side of HVDC Link
U_1	Voltage level at the AC side—node 1 of HVDC Link
U_2	Voltage level at the AC side—node 2 of HVDC Link
θ	Voltage phase angle between the two AC nodes
X	X the reactance of the line between the two AC nodes
L_c	Phase—reactor inductance of the VSC
i_{dq}	Current associated with the converter (in the d-q plane)
u_{dq}	Voltage associated with the VSC converter control loop
ΔP	Small changes of active power at the level of the converter station
ΔQ	Small changes of reactive power at the level of the converter station
U_{0f}	Converter station AC filter voltage level
Δi_{cd}	Small changes of the current in the d axis at the level of the converter station.
Δi_{cq}	Small changes of the current in the q axis at the level of the converter station.
v_{refd}	Reference voltages in d axis
v_{refq}	Reference voltages in q axis
ωt	Angular speed
S_d	Commutation device switch (dissipation device)
R_d	Impedance of the dissipation device
S_c	Commutation device switch (commutating device)
Z_c	Impedance of the commutating device
V_b	Counter-voltage
i_d	Current through the DC circuit breaker before the commutation process
R_V	Surge arrester resistance
$v_{pa,b,c}$	Voltage drops over the submodules of the positive pole (MMC)
$i_{pa,b,c}$	Currents through the submodules of the positive pole (MMC)
$v_{na,b,c}$	Voltage drops over the submodules of the negative pole (MMC)
$i_{na,b,c}$	Currents through the submodules of the negative pole (MMC)

4.2. CSC-HVDC Control Methods and Strategies

One of the main characteristics of HVDC technology is the ability to control the active power flow, both in terms of magnitude and direction. The flow of the active power can be controlled either by changing the DC voltage U_d or the DC current I_d associated with the DC link [36–38].

Figure 10 shows the operating modes of the LCC converter either as an inverter or rectifier.

Usually, in a CSC-HVDC, connection the converter substation operating as an inverter controls the DC voltage U_d , keeping it at a constant value (and strongly related to the value of the AC voltage), and the converter substation acting as a rectifier regulates the DC voltage so that the current I_d flowing through the DC link corresponds to the active power P_d [39,40].

The active power on the DC line always flows from the positive voltage converter pole with the higher value to the positive voltage converter pole with the lower value, and similarly for the negative poles of the connection.

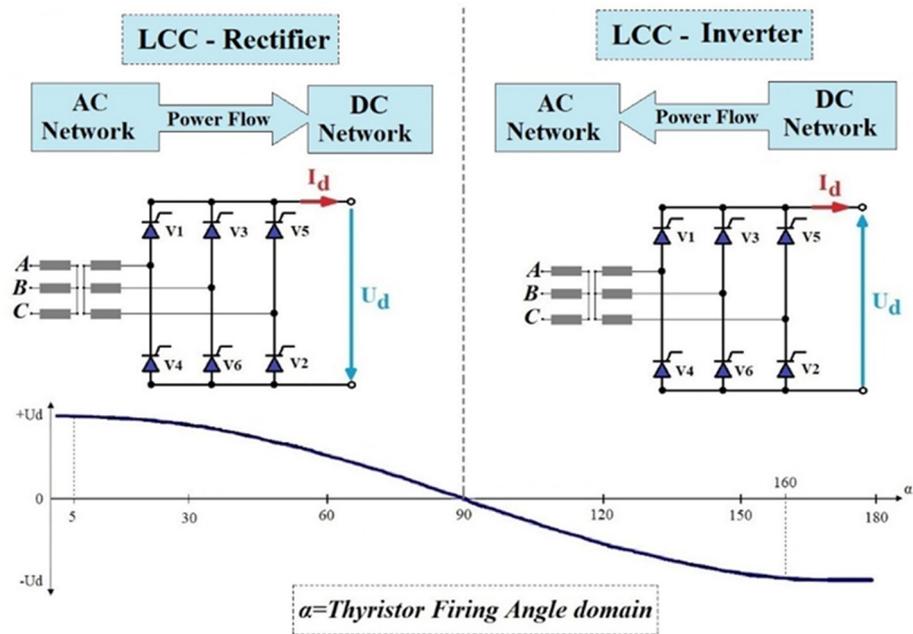


Figure 10. CSC-HVDC Converter operating modes.

The active power (P_d) transferred by the HVDC connection is equal to the product between the DC voltage (U_d) and the current (I_d); therefore, the magnitude of the power on the DC link can be increased either by increasing the voltage provided by the rectifier or by decreasing the voltage from the inverter (by varying the thyristor firing angle values).

$$P_{dr} = U_{dr}I_d \tag{1}$$

$$P_{di} = U_{di}I_d = P_{dr} - (R_L + R_{cr} - R_{ci})I_d^2 \tag{2}$$

$$I_d = \frac{U_{dr} - U_{di}}{R_L}; R_{cr} = \frac{3X_{kr}}{\pi}; R_{ci} = \frac{3X_{ki}}{\pi} \tag{3}$$

P_{dr}, P_{di} —active power at the level of rectifier and inverter;

U_{dr}, U_{di} —DC voltage at the level of rectifier and inverter;

I_d —current through the DC link;

R_{cr}, R_{ci} —commutation resistance at the level of rectifier and inverter;

R_L —resistance of the DC link;

X_{kr}, X_{ki} —short-circuit reactance at the level of rectifier and inverter.

The direction of the active power transferred by the HVDC connection is reversed by changing the polarity of the terminal’s voltages. A particular aspect of CSC–HVDC operation is the fact that I_d doesn’t change its direction.

In Figure 11 the ideal voltage–current characteristics of the two converters (rectifier and inverter) are presented. U_d and I_d can be measured at the same point on the DC line. The characteristics of the inverter and the rectifier are made based on the measurements at the rectifier [39,40].

Both the inverter and the rectifier are equipped with a fast current regulator, with a reference value of I_{0i} for the inverter and I_{0r} for the rectifier (I_{0i} is smaller than I_{0r}), Figure 12a. The value $\Delta I_m = I_{0r} - I_{0i}$ is called the current margin, and it has a value of 0.1–0.15 p.u. of the desired DC current value.

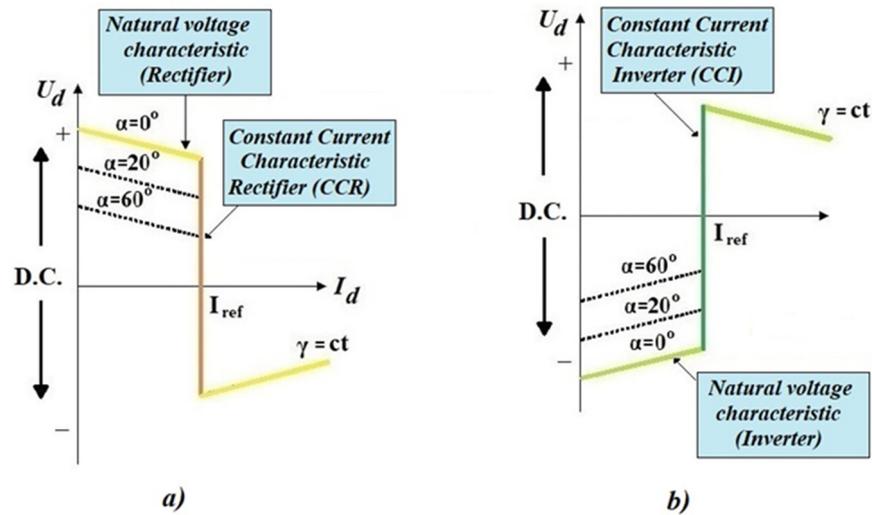


Figure 11. LCC-HVDC-U-I ideal characteristics (a) rectifier, (b) inverter.

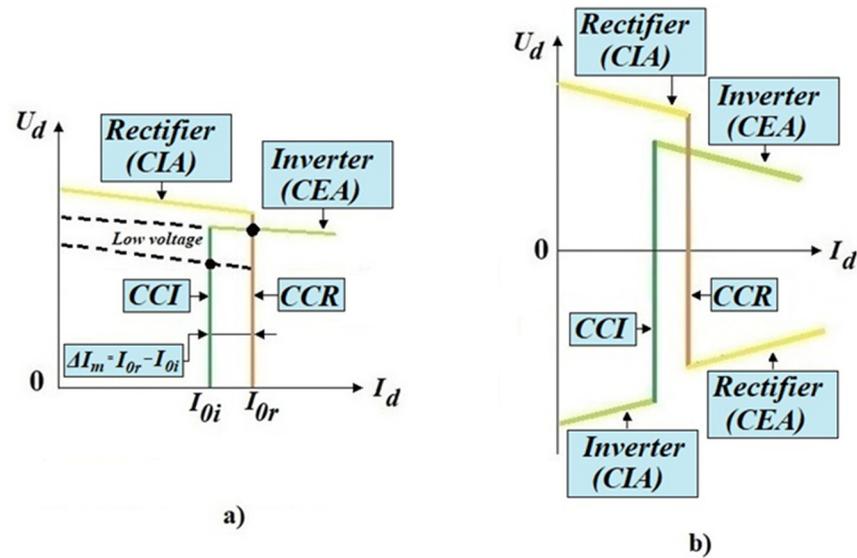


Figure 12. LCC-HVDC-U-I steady-state characteristics (a) steady-state operation; (b) combined operation.

The CSC-HVDC converters have the following operating domains [39,40]:

- CCR—constant-current characteristic rectifier
- CCI—constant-current characteristic inverter
- CIA—constant ignition angle (α)
- CEA—constant extinction angle (γ)

In the case of most CSC-HVDC systems, each of the converters can operate either as a rectifier or as an inverter; therefore, a combined characteristic can be analyzed.

Under normal operating conditions, the rectifier controls the direct current I_d , and the inverter controls the direct voltage U_d , resulting in CCR operating mode (constant current obtained by the rectifier).

4.3. VSC-HVDC Control Methods and Strategies

The main control methods used in VSC-HVDC systems are the “power angle” control strategy and “vector current” control strategy [41].

4.3.1. “Power Angle” Control Strategy

“Power angle” control, also called “voltage angle”, is probably the most direct method possible for controlling VSC-HVDC links. A simplified control scheme usually used for this strategy is presented in Figure 13 [41–43].

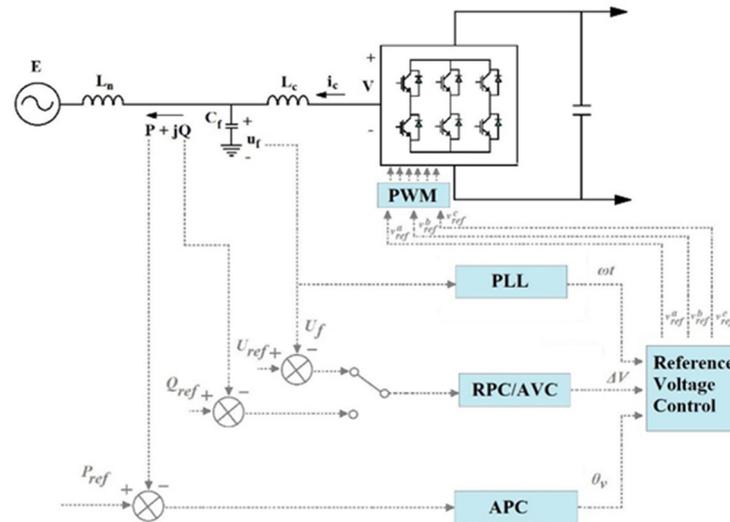


Figure 13. VSC-HVDC “power angle” control strategy.

The “power angle” method is based on the following well-known equations [41–43]:

$$P = \frac{U_1 U_2 \sin \theta}{X} \quad (4)$$

$$Q = \frac{U_1^2 - U_1 U_2 \cos \theta}{X} \quad (5)$$

where P and Q are the active power and the reactive power, respectively, at the level of two AC nodes with the associated voltages U_1 and U_2 ;

θ and X are the voltage phase angle and the reactance of the line between the two AC nodes, respectively.

The basic principle of the “power angle” control method is the following: the active power is controlled by changing the phase angle θ of the voltage associated with the VSC-HVDC connection, while the reactive power is controlled by changing the magnitude of the voltage of the VSC-HVDC connection [41–43].

In order to produce the tri-phase alternating voltage, the VSC-type device needs the following three control variables: magnitude, the phase angle, and the AC frequency. By using the “power angle” control method, the three variables are given by three different control loops, plus an additional synchronization loop, as follows [41–43]:

- RPC (reactive power control)
- AVC (active voltage control)
- APC (active power control)
- PLL (phase-locked loop)

4.3.2. “Vector Current” Control Strategy

The “vector-current” control strategy consists of controlling the current associated with the VSC-HVDC converter station. It was first used in variable speed drives, where the VSC is connected to an AC motor [41–43].

In the case of VSC-HVDC-type connections, the “vector-current” control strategy consists of the independent control of the active and reactive power by means of the following cascaded loops: external control loops and the inner current control loop.

The essence of vector current control is that the control system creates a converter d-q frame, where a PLL is applied to make sure that the d-axis of the converter d-q frame is always aligned with the filter bus voltage in order to synchronize the VSC with the AC system.

The principle of the method is based on the equations of the dynamic operation of the phase reactor associated with the VSC-HVDC connection, resulting by application the Kirchhoff equations in the d-q plane. The mathematical relationship between active and reactive power and current results from the decomposition in the two components of axis d and q, as follows [41–43]:

$$L_c \frac{di_{dq}}{dt} = u_{dq} - u_{fdq} - j\omega L_c i_{cdq} \tag{6}$$

$$\begin{cases} \Delta P = U_f^0 \Delta i_{cd} \\ \Delta Q = -U_f^0 \Delta i_{cq} \end{cases} \tag{7}$$

L_c —phase - reactor inductance of the VSC;
 i_{dq} —current associated with the converter (in the d-q plane);
 u_{dq} —voltage associated with the VSC converter control loop;
 $\Delta P, \Delta Q$ —small changes of active/reactive power at the level of the converter station;
 U_f^0 —converter station AC filter voltage level;
 $\Delta i_{cd}, \Delta i_{cq}$ —small changes of the current in the d and q axis, respectively, at the level of the converter station.

Compared to the “power angle”-type control method, which uses as input quantities $\Delta V, \theta_V$, and ωt , by means of which the three-phase reference voltages of the VSC-HVDC converter are generated, the “vector current” control method works in a similar fashion, using as inputs the reference voltages in axis d and q are as follows: v_{refd}, v_{refq} , and ωt [41–43].

Figure 14 shows a simplified control scheme of the “vector current” control strategy applied to a VSC-HVDC converter station:

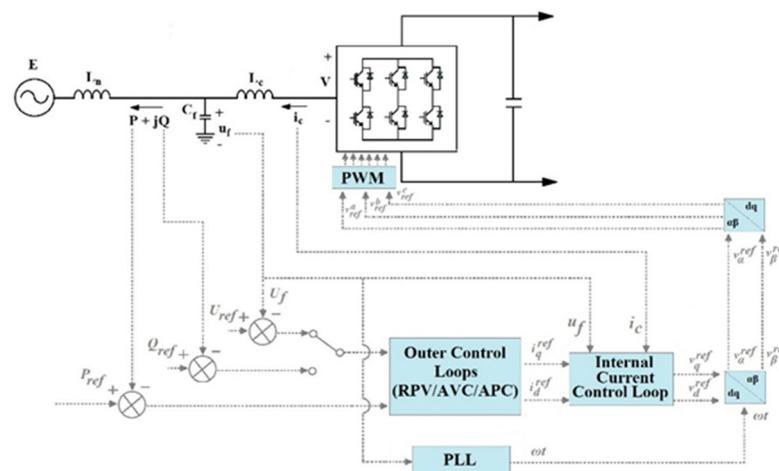


Figure 14. VSC-HVDC “vector current” control strategy.

Therefore, the implementation of a “vector current” control strategy is more complex than the “power angle” strategy, but it manages to cover the shortcomings of the latter, being able to attenuate the resonances in the AC system and better limit the currents associated with the converter valves.

The main disadvantage of the vector control system is the difficulty of implementation in a weak AC network [44,45].

5. Key Challenges Arising from the Use of HVDC Systems

The use of HVDC technology creates several issues, which need to be properly addressed.

5.1. DC Circuit Breaker Solutions

The main issue regarding the implementation of circuit breakers (CB) in DC circuits is that there is no natural passage of fault current through zero, as in the case of classical AC systems. In DC circuits, the fault current can be brought to zero only by applying a higher counter voltage (V_b) than the operating voltage of the system [46].

A second problem is the need to dissipate a large amount of energy stored in the inductor of the DC line.

In order to solve those issues, a typical DC breaker arrangement is equipped with two additional circuits besides the main circuit breaker, an energy-absorbing circuit, and a commutating circuit, see Figure 15 [47,48].

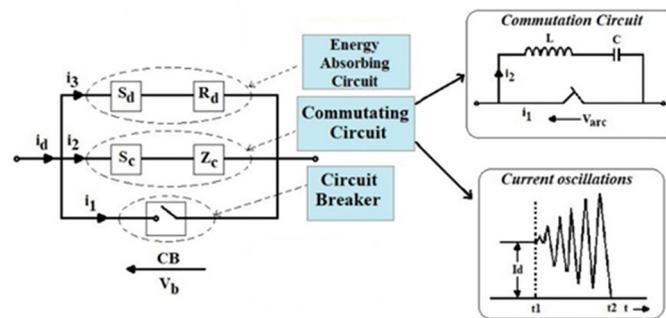


Figure 15. Typical DC circuit breaker arrangement.

At the current moment, the main types of HVDC circuit breakers topologies are the following.

5.1.1. Electromechanical Circuit Breaker

Electromechanical circuit breakers, Figure 16, can be passive or active. Passive technology is older, developed for LCC-HVDC systems.

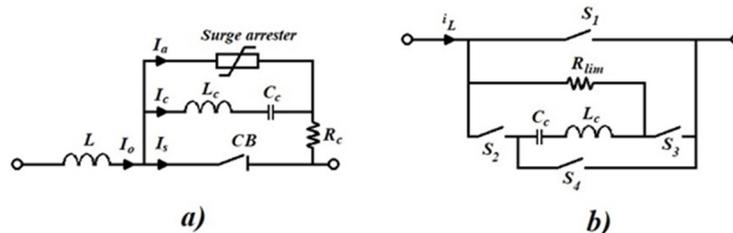


Figure 16. Electromechanical circuit breaker (a) passive, (b) active.

Electromechanical CBs are characterized by large dimensions and masses, as well as a slow response to the opening of the circuit breaker and negligible power losses compared to other circuit breakers at DC [49].

Due to these disadvantages, interest in the utilization of electromechanical breakers has been reduced.

5.1.2. Solid-State Circuit Breakers (SSCB)

Solid-state circuit breakers are characterized by a fast response time, low mass, ease of repair, and maintenance compared to electromechanical circuit breakers.

The main types of solid-state circuit breakers are presented in Figure 17.

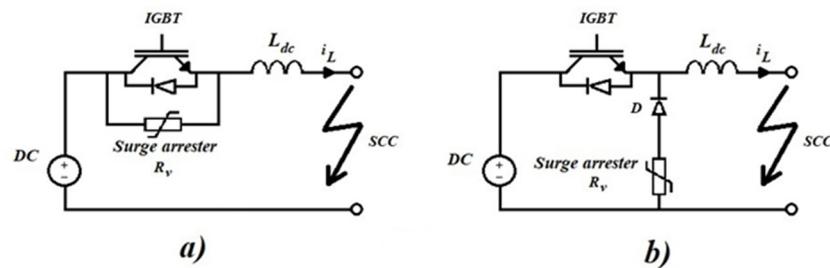


Figure 17. Solid-state circuit breaker (a) CB paralleling a surge arrester, (b) SSCB with a freewheeling diode.

Under normal conditions, current flows from the DC source to the load via the IGBT in the first kind of SSCB; however, when a fault is detected, the semiconductor shuts off. This results in a sharp rise in voltage until the surge arrester begins to conduct. Because of the surge arrester's construction, any voltage higher than the grid voltage is prevented. The second form of SSCB uses a CB in conjunction with a freewheeling diode to bypass any reverse voltage impulse, protecting the IGBT against voltage spikes. It also employs the surge arrester as an absorbing agent for the heat created during the fault, allowing it to be dissipated as rapidly as feasible [50–52].

5.1.3. Hybrid Circuit Breaker

Figure 18 shows an example of a hybrid switch that includes both electromechanical switching devices and solid-state electronics. During normal operation, current flows through both the ultra-fast disconnector (UFD) switch and the load commutation switch (LCS), while the main breaker's current is zero. When a DC fault occurs, the LCS quickly commutates the current to the main DC breaker, which functions similarly to a solid-state CB, and the UFD switch opens. The UFD maintains low voltage loss while allowing for quick switching. The primary DC breaker cuts the electricity when the mechanical switch is in the open position [53–55].

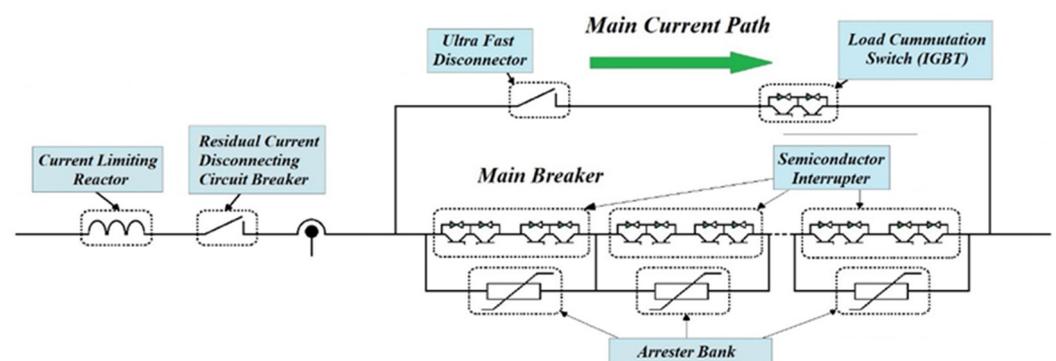


Figure 18. Hybrid circuit breaker.

During zero current and low voltage stress, the mechanical switch opens. After remaining in an open state while the main DC breaker opens, the fast disconnector will be exposed to the recovery voltage determined by the protection level of the arrester banks first [53–55].

Among the main developers that came up with improved versions of the hybrid circuit breaker is ABB. Figure 18 shows the general scheme of a hybrid circuit breaker developed by ABB [53–55].

5.2. Reliability and Maintenance of HVDC Converter Substations

Given the rapid advancement of power electronics, a growing number of HVDC projects have been installed across the world. Their reliability and maintenance strategies

have a direct influence on the system’s service security and, as a result, have a significant impact on network operation [55]. Figure 19 shows the impact of the various components on the forced energy unavailability (FEU) indicator, where it can be seen that the converter valves take part in two-thirds of the number of forced outages, resulting in a high requirement for proper maintenance of converter substations, especially converter valves [56,57].

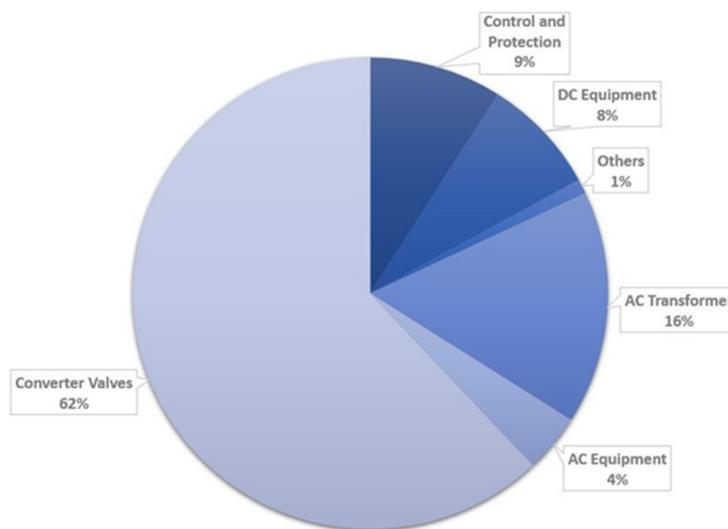


Figure 19. FEU—forced energy utilization for LCC–HVDC.

To better understand the impact of HVDC links, CIGRE has completed biannual reports [58,59] on the reliability and energy utilization of HVDC converter stations.

Figure 20 shows the installation cost breakdown of various components within a converter substation.

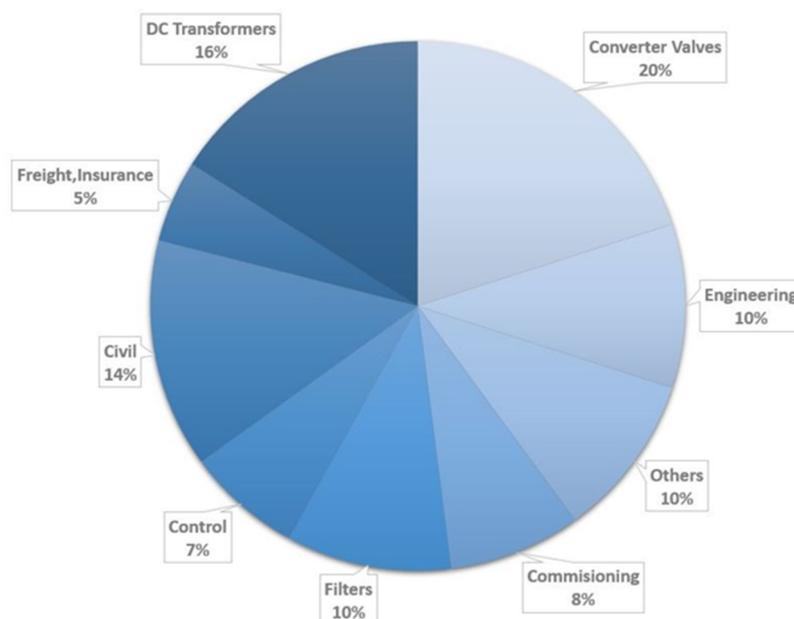


Figure 20. Installation costs—HVDC converter station.

Recently, the emphasis has been on monitoring the operation of the converters in order to maintain proper operation. But due to the complexity of power converter structures and their degradation mechanisms, interpreting the information obtained by this technique (monitoring) is difficult, especially for non-experts [58,59].

The main maintenance strategies deployed for HVDC technologies are presented in Figure 21.

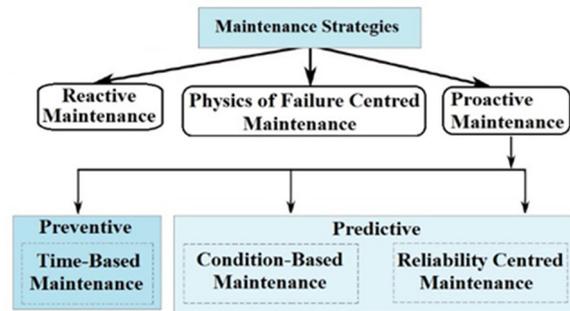


Figure 21. Maintenance strategies.

5.3. Multi-Terminal HVDC System Operation

The operating and control difficulties of MTDC networks are similar to those already present in existing AC networks.

Figure 22 shows a general example of a VSC-HVDC multi-terminal connection used to connect several offshore wind power plants.

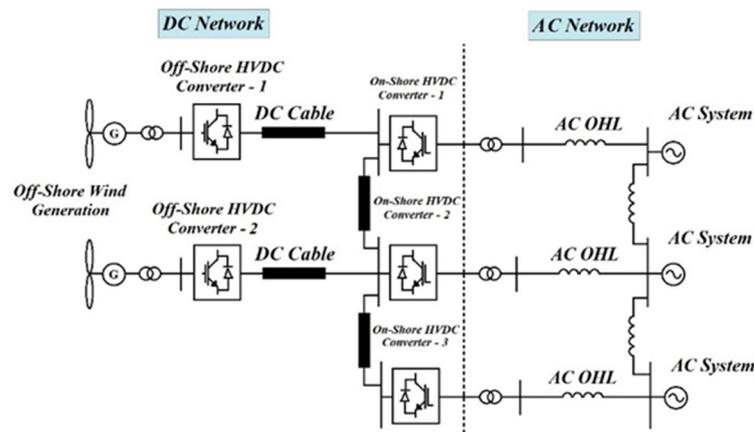


Figure 22. VSC-HVDC multi-terminal connection used to connect offshore wind power plants.

Unlike the classic AC networks, where FACTS-type devices are used for power flow control, in the case of MTDC-type connections, this operation is easier because the control is performed only through the DC current and voltage. Thus, normally in an HVDC link, one of the converters (inverter) controls the DC voltage associated with the connection, while the other (rectifier) controls the active power, and practically, the current flowing through the DC connection. In order to apply this control principle at the level of MTDC connections, it is necessary to integrate particular protection and control systems [60,61].

The main differences that must be considered between the different types of HVDC technologies and their implementation within MTDC networks are the following:

- In a LCC-MTDC configuration, it is absolutely necessary to implement a communication path between the converters to control the power flow and to coordinate the change of voltage polarity in the case of a change in power flow direction at one of the terminals (in the case of LCC-HVDC, DC current flows only in one direction; the change of power direction is achieved by changing the voltage polarity. In the case of VSC-HVDC technology, the voltage polarity never changes, allowing current flow in both directions).
- In a VSC-MTDC configuration, there is no need for communication between terminals; balancing the power flow is achieved by monitoring the system voltage. Therefore, VSC-HVDC technology is better suited for MTDC connections.

6. Future Trends and Applications of HVDC Transmission Systems

6.1. Modular Multilevel Converter (MMC) HVDC

MMC technology was first proposed for HVDC applications in 2003 by Professor Rainer Marquardt, with the first commercial project to use it being the “Trans Bay Cable” in San Francisco. At the moment, the most common technology used in VSC converters is represented by MMC (Modular Multilevel Converter) [62].

In Figure 23, the basic MMC topology for both “half-bridge” and “full-bridge” structures is presented.

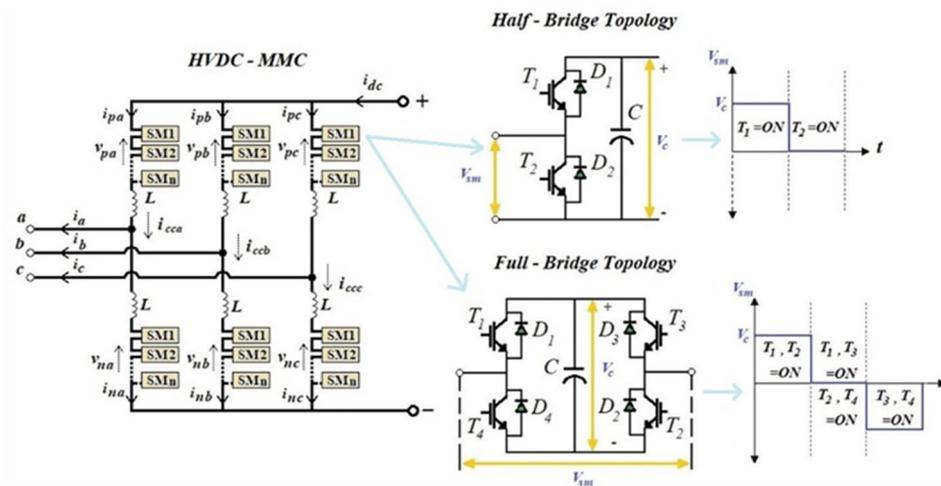


Figure 23. MMC-HVDC “half-bridge” vs. “full-bridge” topology.

Similar to two-level (VSC) and six-pulse (CSC) converters, an MMC converter consists of six valves arranged so that each connects an AC terminal to a DC terminal. However, unlike in the two-level converter, where each valve effectively consists of a high voltage switch consisting of a large number of IGBT devices connected in series, in the case of the MMC converter, each valve is an independent VSC source. Each MMC valve consists of a number of submodules, each containing its own storage capacitor. In the most common form, called the “half-bridge”, each submodule contains two IGBT devices connected in series with each other and with the capacitor, with the midpoint and one of the capacitor terminals forming the output connection of the submodule [63,64].

Another alternative that replaces the “half-bridge” MMC submodules is the “full-bridge submodules”, which contain four IGBTs in an H-type arrangement. The full-bridge configuration allows the insertion of the submodule capacitor into a circuit on each polarity. This gives additional flexibility in the control of the converter, which can block the fault current that may occur in the event of a short circuit between the positive and negative terminals of the terminals at DC (operation is impossible with other VSC configurations) [65].

6.2. Cascaded Two-Level (CTL) HVDC

An alternative to the MMC converter, proposed by one of the manufacturers, consists of connecting several IGBT devices in series on each of the two switches of the submodule.

Each phase leg of the CTL converter is divided into the following two arms: positive and negative, which respectively connect the positive and negative poles of the DC bus to the converter’s AC bus. Each arm is built as a cascade of N two-level-converter cells.

The cascaded two-level cells in each arm are controlled to provide a fundamental-frequency output voltage, related to the desired active- and reactive-power output, through switching of the individual cells.

Functionally, it is approximately equivalent to the half-bridge MMC in all respects except for harmonic distortion, which is more pronounced in the case of CTL, but low enough so that it doesn’t require additional filters [66].

Figure 24 shows the topology of the CTL converter deployed by ABB [66–69].

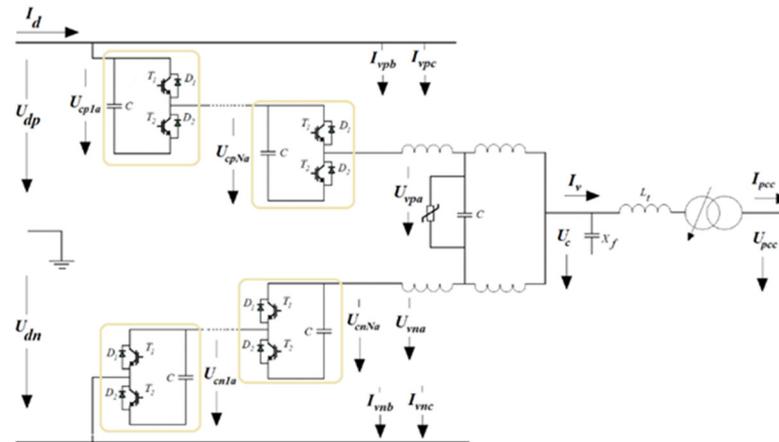


Figure 24. CTL-HVDC Topology (ABB).

6.3. Classical Hybrid VSC-CSC HVDC Links

A super-network is currently being planned in Europe, in which the transmission systems will play a vital role. Figure 25 shows a hybrid VSC-CSC HVDC link.

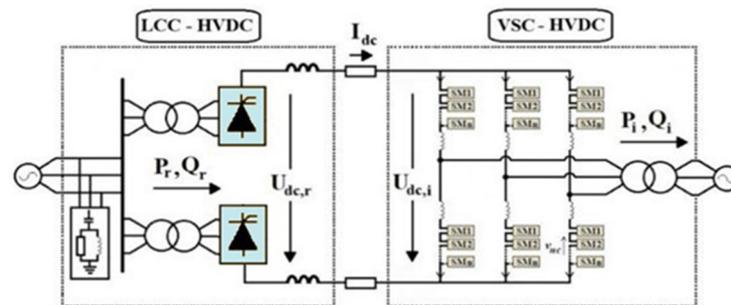


Figure 25. Hybrid VSC-CSC HVDC link.

An important number of VSC-HVDC connections have already been made and implemented in Europe, but the high cost of this technology could slow down the development of an interconnected super-network.

In this context, HVDC manufacturers are investing in cost reduction solutions by using only a low-level power electronics component, especially in the case of integrating VSC-HVDC systems into offshore wind power plants.

HVDC hybrid systems, Figure 25, containing both LCC and VSC converters, are an alternative that combines the following advantages of both conversion technologies: lower investment costs and power losses in the case of LCC technologies, and the flexibility and advanced control capabilities of active and reactive power flow of VSC technology [70–73].

6.4. Recent HVDC Innovations and Developments

Some of the recent innovations in HVDC technologies consist of new types of HVDC topologies, converter technologies, and the use of HVDC technologies in order to optimize network operation.

6.4.1. New VSC- HVDC Bipolar Topologies

- Pseudo-bipolar HVDC link

In a pseudo-bipolar HVDC transmission system, the HVDC cables are linked to only one converter at each ending terminal. As illustrated in Figure 26, the two-level or three-level converter types VSC-HVDC are grounded by a capacitor, although the MMC converter

type VSC doesn't need to be grounded via a capacitor. The earth point is located between the positive and negative lines of the converter in the pseudo bipolar HVDC transmission system, with no direct current passing via the ground point but returning through the negative cable (Figure 26). In the case of unavailability, one of the DC cables fails, and the other cable becomes inoperable too [74].

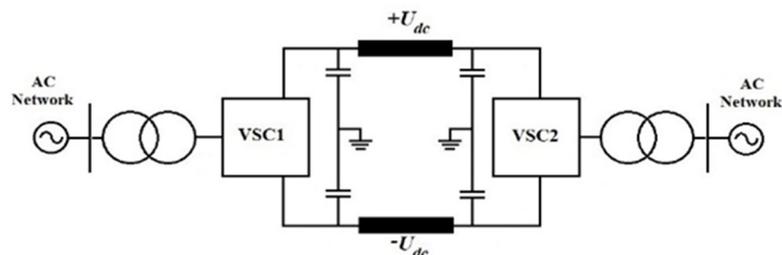


Figure 26. VSC-HVDC—pseudo-bipolar connection.

- *True bipolar HVDC link*

Each direct current DC cable of a true bipolar HVDC transmission system is linked to an individual converter. The earth point of the true bipolar HVDC system is fixed at a single position in each station, as indicated in Figure 27.

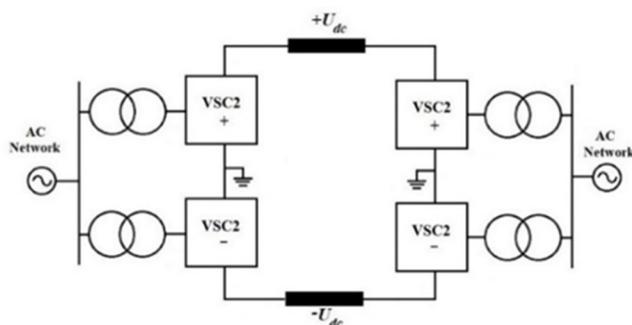


Figure 27. VSC-HVDC—true bipolar connection.

It provides independent control for the positive and negative poles and the following features when compared to the pseudo bipolar VSC-HVDC:

(1) The positive-pole and negative-pole networks operate independently. This topology allows the system to function in both an asymmetric true bipolar mode and an asymmetric mode, in which the current flowing through the positive pole network is greater than the current flowing through the negative pole network.

(2) Increased reliability. For the positive-pole and negative-pole networks, the true bipolar VSC-MTDC contains two independent converters. When a contingency occurs or routine maintenance is performed on the DC side of a single pole, only one pole is impacted, while the other pole can continue to work properly; therefore, half of the capacity of the link can still be transmitted [74].

- *Hybrid bipolar HVDC link*

When the pseudo and true bipolar HVDC transmission systems are combined, a hybrid bipolar HVDC system topology emerges, as illustrated in Figure 28. However, for large-scale renewable power integration via MTDC transmission systems, more research is required on the control strategy and topology of the bipolar MTDC transmission system [74].

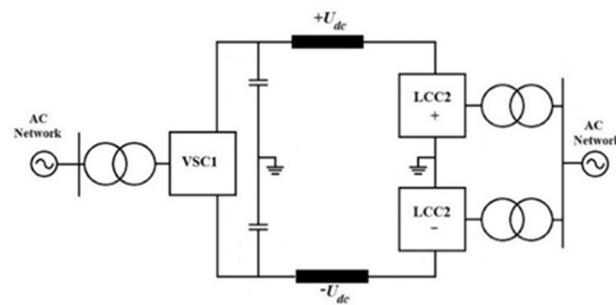


Figure 28. Hybrid bipolar HVDC transmission system.

6.4.2. Flexible LCC Converter

Flexible LCCs use a controllable capacitor to enhance LCC characteristics, resulting in improved harmonic filtering and a significant reduction of the HVDC station footprint. Furthermore, commutation failure can be eliminated with a lower voltage rating and capacitance of the controllable capacitors (compared with traditional LCCs). Figure 29 illustrates a type of six-pulse flexible LCC topology [74].

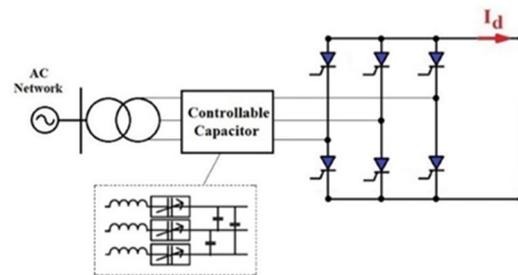


Figure 29. Flexible LCC converter topology.

6.4.3. Use of VSC-HVDC for Voltage Stabilization and Transient Stabilization

VSC-HVDC has grown in popularity in recent years as a means of improving the stability of current AC grids. Voltage and frequency instabilities, power swings, and transients are the main potential sources of instabilities in AC grids.

To prevent this from happening or to suppress it all together, a range of methods are used, such as imposing operating constraints on transmission capacity or installing phase-modifying equipment.

Moreover, many locations, particularly those suitable for large renewable energy projects, are prone to instability due to vulnerabilities in existing local grids and a lack of short-circuit capacity, implying that increased renewable penetration frequently necessitates additional measures to address these instabilities. Installation of VSC-HVDC at such sites can assist in stabilizing the local grid in addition to offering a mechanism to transport renewable energy to demand regions. In [75] a means of voltage control is presented with a visual example. Voltage fluctuations are reduced when the AC voltage is controlled in this manner [75].

7. Conclusions

This paper reviews the current state of HVDC technology and the recent developments seen in HVDC converter topologies. In conclusion, it identifies the following key technical challenges of the main aspects of HVDC technology:

- The most used applications of HVDC technologies are summarized as the following: long-distance bulk power transmission, submarine cable transmission, asynchronous ties, offshore wind power plant transmission, and multi-terminal HVDC systems;

- At the moment, the main types of HVDC topologies used are the monopolar link, bipolar link (both with metallic return conductor or ground return path), back-to-back link, and homopolar link;
- The primary components of the HVDC converter stations are presented for both VSC technology (particularly the use of phase reactor and DC capacitors) and CSC technology (particularly the use of DC and AC filters);
- The main control strategies and U-I characteristics used for CSC-HVDC control are summarized (CCR, CCI, CIA, and CEA). Also, the main strategies for VSC-HVDC (power angle and vector control strategies) are presented with the associated active and reactive power control loops and the PLL loop (phase-locked loop) implementation;
- Furthermore, the following series of key challenges arising from the use of HVDC technologies are discussed: DC circuit breaker solutions (the main types of existing circuit breakers are as follows: electromechanical, solid-state, and hybrid circuit breakers are presented), reliability and maintenance of HVDC converter substation, multi-terminal operation;
- The study also takes a look at the future trends and applications of HVDC technologies such as MMC, CTL converters, hybrid implementation of HVDC links, new types of bipolar topologies, and network stability improvement applications of HVDC technology;

Future Considerations and Developments:

HVDC technology will play a more important role for increased implementation of renewable energy and enhancement of the security and reliability in complex operational conditions.

- One of the challenges of VSC-HVDC technology that needs to be addressed in the near future is increasing the transfer capacity of the cables. At the moment, superconducting cables are being researched in order to achieve a transfer capacity higher than 3 GW, which will make VSC-HVDC a viable option for bulk power transmission.
- Seeing the increase in renewables in modern networks, another challenge related to power system stability that will be addressed by the implementation of VSC-HVDC links is the synthetic inertia and fast frequency support. Modern converters must have a control system calibrated in order to respond as fast as possible to the changes in the AC network;
- Considering an increase in the spread of the use of HVDC technology, the reliability of the power electronics devices needs to be improved. One of the technologies that will enable us to improve the reliability of HVDC systems is condition and health monitoring, which will improve the estimation of the state-of-health and end-of-life of the power electronic devices;
- In order to reduce the cost of the converters and also improve the reliability and conduction losses, SiC semiconductor technology (Silicon-Carbide-Based) should be implemented in future HVDC projects. At the moment, SiC technology is being researched for HVDC systems.

At the moment, in the National Power System (NPS) of Romania, there is no HVDC connection implemented, but several preliminary feasibility studies have been performed. Within my research team, we want to analyze the impact of a VSC-HVDC connection on the stability of the Romanian transmission network, both during the steady-state and dynamic operation of the system.

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References

1. Peake, O. The history of high voltage direct current transmission. *Aust. J. Multi-Discip. Eng.* **2010**, *8*, 47–55. [\[CrossRef\]](#)
2. Asplund, G.; Carlsson, L.; Tollerz, O. 50 years HVDC Part I, ABB – from pioneer to world leader. *ABB Rev.* **2003**, *4*, 6–13.
3. Haglöf, L. *HVDC Veterans' Presentations—The History of HVDC Part 1: The Mercury Arc Valve Era*; HVDC 50 years: Presentation at the Gotland seminar, 6 May 2004; ABB: Zürich, Switzerland, 2004.
4. Melhem, Z. *Electricity Transmission, Distribution and Storage Systems*; Woodhead Pub: Oxford, UK, 2013.
5. Okba, M.H.; Saied, M.H.; Mostafa, M.Z.; Abdel Moneim, T.M. High voltage direct current transmission—A review, part I. In Proceedings of the 2012 IEEE Energytech, Cleveland, OH, USA, 29–31 May 2012; pp. 1–7. [\[CrossRef\]](#)
6. Flisberg, G.; Carlsson, C.; Moni, R.; Boveri, A. *Global Trends in Bulk Power Transmission*; ABB Group: Ludvika, Sweden, 2009.
7. Bahrman, M.; Johnson, B. The ABCs of HVDC transmission technologies. *IEEE Power Energy Mag.* **2007**, *5*, 32–44. [\[CrossRef\]](#)
8. Andersen, B.; Barker, C. A new era in HVDC? *IEEE Rev.* **2000**, *46*, 33–39. [\[CrossRef\]](#)
9. Liu, Z.; Zhang, F.; Yu, J.; Gao, K.; Ma, W. Research on key technologies in ± 1100 kV ultra-high voltage DC transmission. *High Volt.* **2018**, *3*, 279–288. [\[CrossRef\]](#)
10. Meier, A. *Electric Power Systems*, 1st ed.; Wiley: Hoboken, NJ, USA; IEEE Press: Piscataway, NJ, USA, 2006.
11. Setréus, J.; Eriksson, R.; Karlsson, S.; Swaitti, O.; Leelaruji, R.; Yu, L. *Study visit at the SwePol HVDC Link*; Royal Institute of Technology (KTH), School of Electrical Engineering: Stockholm, Sweden, 2006.
12. Skog, J.; Koreman, K.; Pääjärvi, B.; Andersröd, T. *The Normed HVDC Cable Link—A Power Transmission Highway between Norway and The Netherlands*; ENERGEX: Stavanger, Norway, 2006.
13. Pourbeik, P.; Bahrman, M.; John, E.; Wong, W. Modern countermeasures to blackouts. *IEEE Power Energy Mag.* **2006**, *4*, 36–45. [\[CrossRef\]](#)
14. Wang, H.; Redfern, M.A. The advantages and disadvantages of using HVDC to interconnect AC networks. In Proceedings of the 45th International Universities Power Engineering Conference (UPEC), Cardiff, UK, 31 August–3 September 2010; pp. 1–5.
15. Dong, C.; Zhang, H.; Li, Y.; Jiang, W.; Gao, X. Security and stability control strategy of Gaoling back-to-back HVDC project. *Dianwang Jishu Power Syst. Technol.* **2015**, *39*, 1240–1245.
16. Kirby, N.; Siepmann, W.; Xu, L.; Luckett, M. HVDC transmission for large offshore wind farms. *Power Eng. J.* **2002**, *16*, 135–141. [\[CrossRef\]](#)
17. Muyeen, S.M.; Takahashi, R.; Tamura, J. Operation and control of HVDC-connected offshore wind farm. *IEEE Trans. Sustain. Energy* **2010**, *1*, 30–37. [\[CrossRef\]](#)
18. GE Grid Solutions. *DolWin3 HVDC Voltage Source Converters for Efficient Connection of Renewable Energy*; GE Grid Solutions: Stafford, UK, 2018.
19. UL. *Offshore Wind Energy in Germany Status 31.12.2018 and Prospects until 2030*; UL—Empowering Trust: Northbrook, IL, USA, 2018.
20. Bahrman, M.P. HVDC transmission overview. In Proceedings of the 2008 IEEE/PES Transmission and Distribution Conference and Exposition, Chicago, IL, USA, 21–24 April 2008; pp. 1–7. [\[CrossRef\]](#)
21. Chen, Y. Review of the development of multi-terminal HVDC and DC power grid. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *93*, 012044. [\[CrossRef\]](#)
22. Rodriguez, P.; Rouzbehi, K. Multi-terminal DC grids: Challenges and prospects. *J. Mod. Power Syst. Clean Energy* **2017**, *5*, 515–523. [\[CrossRef\]](#)
23. Chitode, J.S. *Power Electronics*, 4th ed.; Technical Publications: Maharashtra, India, 2009.
24. Kuruganty, S. HVDC transmission system models for power system reliability evaluation. In Proceedings of the IEEE WESCANEX 95: Communications, Power, and Computing Conference, Winnipeg, MB, Canada, 15–16 May 1995; Volume 2, pp. 501–507. [\[CrossRef\]](#)
25. Billinton, R.; Fotuhi-Firuzabad, M.; Faried, S.O.; Aboreshaid, S. Composite system reliability evaluation incorporating an HVDC link and a static synchronous series compensator. In Proceedings of the IEEE CCECE2002: Canadian Conference on Electrical and Computer Engineering (Cat. No. 02CH37373), Winnipeg, MB, Canada, 12–15 May 2002; Volume 1, pp. 42–47. [\[CrossRef\]](#)
26. Singh, M.D.; Khanchandai, K.B. *Power Electronics*, 2nd ed.; Tata McGraw-Hill Publishing Company Limited: New York, NY, USA, 2008.
27. Zhang, C. *UHV Transmission Technology*; Edited by The China Electric Power Research Institute; Elsevier Science: Amsterdam, The Netherlands, 2018.
28. Sivanagaraju, S.; Satyanarayana, S. *Electric Power Transmission and Distribution*; Dorling Kindersley: New Delhi, India, 2012.
29. Sood, V. *HVDC and FACTS Controllers: Applications of Static Converters in Power Systems*; Kluwer Academic Publishers: Amsterdam, The Netherlands, 2004.

30. Retzmann, D.; Siemens, A.G. *HVDC Station Layout, Equipment LCC & VSC and Integration of Renewables Using HVDC*; Cigré Tutorial; CIGRE: Paris, France, 2012.
31. Alstom, H.V.D.C. *HVDC for Beginners and Beyond*; Alstom: Saint-Ouen, France, 2010.
32. Csutar, V.G.; Kallikuppa, S.; Charles, L. *Introduction to HVDC Architecture and Solutions for Control and Protection*; Texas Instruments: Dallas, TX, USA, 2020.
33. Jonsson, T. *High Power Electronics for HVDC Power Transmission*; TSTE19 Power Electronics Lecture 14; ABB Grid Systems: Västerås, Sweden, 2015.
34. Roy, R.; Amin, M. A paper of determination of controlling characteristics of the monopolar HVDC system. *Int. J. Hybrid Inf. Technol.* **2014**, *7*, 105–120. [[CrossRef](#)]
35. Brand, L.; de Silva, R.; Bebbington, E.; Chilukuri, K. *Grid West Project HVDC Technology Review*; EirGrid, PSC Specialist Consultants for Electricity Industry: Dublin, Ireland, 2014.
36. Larruskain, D.M.; Zamora, I.; Mazón, A.; Abarrategui, O.; Monasterio, J. Transmission and distribution networks: AC versus DC. In Proceedings of the 9th Spanish Portuguese Congress on Electrical Engineering, Marbella, Spain, 30 June–2 July 2005.
37. Setréus, J.; Bertling Tjernberg, L. Introduction to HVDC technology for reliable electrical power systems. In Proceedings of the 10th International Conference on Probabilistic Methods Applied to Power Systems, Rincon, Puerto Rico, 25–29 May 2008; pp. 1–8.
38. Eremia, M.; Liu, C.-C.; Edris, A.-A. *Advanced Solutions in Power Systems: HVDC, FACTS, and Artificial Intelligence*; IEEE Press: Piscataway, NJ, USA; Wiley: Hoboken, NJ, USA, 2016.
39. Lluch, J.R. Modelling, Control and Simulation of LCCHVDC Systems for Stability Studies. Master's Thesis, Escola Tècnica Superior d'Enginyeria Industrial de Barcelona, Barcelona, Spain, June 2017.
40. Yin, H. Modeling and Control of Wind Generation and Its HVDC Delivery System. Ph.D. Thesis, University of South Florida, Tampa, FL, USA, 2011.
41. Zhang, L. Modeling and Control of VSC–HVDC Links Connected to Weak AC Systems. Ph.D. Thesis, Royal Institute of Technology, School of Electrical Engineering Electrical Machines and Power Electronics, Stockholm, Sweden, 2010.
42. Zheng, X.; Li, Y.; Liu, Z.; Wang, C. Steady-state control strategy of VSC-HVDC transmission system based on full-order terminal sliding mode control method. *J. Eng.* **2019**, *2019*, 987–990. [[CrossRef](#)]
43. Stan, A.; Stroe, D.; da Silva, R. Control strategies for VSC-based HVDC transmission system. In Proceedings of the 2011 IEEE International Symposium on Industrial Electronics, Gdansk, Poland, 27–30 June 2011; pp. 1387–1392. [[CrossRef](#)]
44. Hannan, M.A.; Hussin, I.; Ker, P.J.; Hoque, M.M.; Lipu, M.H.; Hussain, A.; Rahman, M.A.; Faizal, C.W.M.; Blaabjerg, F. Advanced control strategies of VSC based HVDC transmission system: Issues and potential recommendations. *IEEE Access* **2018**, *6*, 78352–78369. [[CrossRef](#)]
45. Song, R.; Zheng, C.; Li, R.; Zhou, X. VSCs based HVDC and its control strategy. In Proceedings of the 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific, Dalian, China, 18 August 2005; pp. 1–6.
46. Muriuki, J.K.; Muriithi, C.M.; Ngoo, L.; Nyakoe, G. Review of HVDC circuit breakers topologies. *IOSR J. Electr. Electron. Eng.* **2017**, *12*, 109–117. [[CrossRef](#)]
47. Padiyar, K. *HVDC Power Transmission Systems—Technology and System Interactions*, 1st ed.; New Age International Limited: New Delhi, India, 2005.
48. Nakanishi, K. *Switching Phenomena in High-Voltage Circuit Breakers*, 1st ed.; Marcel Dekker, Inc.: New York, NY, USA, 1991.
49. Kostoulas, N.; Sitokonstantinou, V.; Idris, M.; Sterling, P.; Sayed, S.; Karaiskos, P. *DC Circuit Breakers and Their Use in HVDC Grids*; Imperial College London: London, UK, 2011.
50. Etxegarai, A.; Larruskain, D.M.; Abarrategi, O.; Eguia, P.; Buigues, G. HVDC Circuit Breakers for HVDC Grids. *Int. J. Eng. Res. Technol.* **2019**, *8*, 665–670. [[CrossRef](#)]
51. Tristiu, I.; Bulac, C.; Costinas, S.; Toma, L.; Mandiș, A.; Zăbavă, T. A new and efficient algorithm for short-circuit calculation in distribution networks with distributed generation. In Proceedings of the 2015 9th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 7–9 May 2015; pp. 816–821. [[CrossRef](#)]
52. Mohammadi, F.; Rouzbehi, K.; Hajian, M.; Niayesh, K.; Gharehpetian, G.; Saad, H.; Hasan Ali, M.; Sood, V. HVDC circuit breakers: A comprehensive review. *IEEE Trans. Power Electron.* **2021**, *36*, 13726–13739. [[CrossRef](#)]
53. Ahmad, M.; Wang, Z.; Shafique, M.; Nadeem, M.H. Significance of fault-current-limiters and parameters optimization in HVDC circuit breakers for increased capacity of VSC-HVDC transmission networks application. *Energy Rep.* **2022**, *8*, 878–892. [[CrossRef](#)]
54. Zhu, C.; Li, K.; Li, R.; Zhang, H.; Sun, L.; Hu, Y. A new hybrid DC circuit breaker topology. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *188*, 012099. [[CrossRef](#)]
55. Khorasaninejad, M.; Radmehr, M.; Firouzi, M.; Koochaki, A. Application of a resistive mutual-inductance fault current limiter in VSC-based HVDC system. *Int. J. Electr. Power Energy Syst.* **2022**, *134*, 107388. [[CrossRef](#)]
56. Ciupăgeanu, D.; Costinas, S. Improving predictive maintenance for HVDC transmission systems through analytic hierarchy process. In Proceedings of the 2017 International Conference on Energy and Environment (CIEM), Bucharest, Romania, 19–20 October 2017; pp. 26–30. [[CrossRef](#)]
57. Guo, J.; Wang, X.; Bie, Z.; Hou, Y. Reliability modeling and evaluation of VSC-HVDC transmission systems. In Proceedings of the 2014 IEEE PES General Meeting, Conference & Exposition, National Harbor, MD, USA, 27–31 July 2014; pp. 1–5. [[CrossRef](#)]
58. Cochrane, J.; Emerson, M.; Donahue, J.; Wolf, G. A survey of HVDC operating and maintenance practices and their impact on reliability and performance. *IEEE Trans. Power Deliv.* **1996**, *11*, 514–518. [[CrossRef](#)]

59. Georgiana, I.; Costinas, S.; Stan, A. Trends to increase the life cycle of a substation in context of smart grid; Power up our Future; In Proceedings of the 10th International Conference on Energy and Environment CIEM 2021, Bucharest, Romania, 14–15 October 2021.
60. Tang, G.; Luo, X.; Wei, X. *Multi-Terminal HVDC and DC-Grid Technology*; Chinese Society for Electrical Engineering: Beijing, China, 2013; Volume 33, pp. 8–17.
61. Zhu, J.; Booth, C. Future multi-terminal HVDC transmission systems using voltage source converters. In Proceedings of the 45th International Universities Power Engineering Conference (UPEC), Cardiff, UK, 31 August–3 September 2010; pp. 1–6.
62. Beddard, A.; Barnes, M. Modelling of MMC-HVDC systems—An overview. *Energy Procedia* **2015**, *80*, 201–212. [[CrossRef](#)]
63. Gomis-Bellmunt, O.; Liang, J.; Hertem, D. *HVDC Grids: For Offshore and Supergrid of the Future*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2016.
64. Zhang, B.; Zhao, C.; Guo, C.; Xiao, X.; Zhou, L. Controller architecture design for MMC-HVDC. *Adv. Electr. Comput. Eng.* **2014**, *14*, 9–16. [[CrossRef](#)]
65. Sharifabadi, K.; Harnefors, L.; Nee, H.; Norrga, S.; Teodorescu, R. *Design, Control, and Application of Modular Multilevel Converters for HVDC Transmission Systems*, 1st ed.; Wiley: Hoboken, NJ, USA; IEEE Press: Piscataway, NJ, USA, 2016.
66. Jacobson, B.; Karlsson, P.; Asplund, G.; Harnefors, L.; Jonsson, T. *VSC-HVDC Transmission with Cascaded Two-Level Converters*; ABB Sweden: Zürich, Switzerland; CIGRE: Paris, France, 2010.
67. Acha, E.; Jaén, A.; Kazemtabrizi, B.; Castro, L.; Roncero-Sánchez, P. *VSC-FACTS-HVDC: Analysis, Modelling and Simulation in Power Grids*, 1st ed.; Wiley: Hoboken, NJ, USA, 2019.
68. Li, B.; Li, J. Probabilistic sizing of a low-carbon emission power system considering HVDC transmission and microgrid clusters. *Appl. Energy* **2021**, *304*, 117760. [[CrossRef](#)]
69. Echeverría, J.; Kouro, S.; Pérez, M.; Abu-rub, H. Multi-modular cascaded DC-DC converter for HVDC grid connection of large-scale photovoltaic power systems. In Proceedings of the IECON 2013—39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10–13 November 2013; pp. 6999–7005. [[CrossRef](#)]
70. Cheah-Mane, M.; Song, J.; Ferrer-San-Jose, R.; Prieto-Araujo, E.; Gomis-Bellmunt, O. Analysis of hybrid LCC-VSC HVDC transmission system configurations. In Proceedings of the 15th IET International Conference on AC and DC Power Transmission (ACDC 2019), Coventry, UK, 5–7 February 2019; pp. 1–6. [[CrossRef](#)]
71. Sun, P.; Wickramasinghe, H.R.; Konstantinou, G. Hybrid LCC-AAC HVDC transmission system. *Electr. Power Syst. Res.* **2021**, *192*, 106910. [[CrossRef](#)]
72. Xiao, H.; Sun, K.; Pan, J.; Li, Y.; Liu, Y. Review of hybrid HVDC systems combining line communicated converter and voltage source converter. *Int. J. Electr. Power Energy Syst.* **2021**, *129*, 106713. [[CrossRef](#)]
73. Perez-Molina, M.J.; Larruskain, D.M.; Lopez, P.E.; Buigues, G.; Valverde, V. Review of protection systems for multi-terminal high voltage direct current grids. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111037. [[CrossRef](#)]
74. Wang, M.; An, T.; Ergun, H.; Lan, Y.; Andersen, B.; Szechtman, M.; Leterme, W.; Beerten, J.; Van Hertem, D. Review and outlook of HVDC grids as backbone of the transmission system. *CSEE J. Power Energy Syst.* **2021**, *7*, 797–810.
75. Nishioka, A.; Alvarez, F.; Omori, T. Global Innovation Report—Global Rise of HVDC and Its Background. *Hitachi Rev.* **2021**, *69*, 462–463.