Proceedings of the 2023 International Conference on Machine Learning and Automation
DOI: 10.54254/2755-2721/42/20230682

Advancements and comparative analysis of high-voltage direct current transmission technologies

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Abstract. This paper outlines the fundamental principles of high-voltage direct current (HVDC) transmission, elucidating its two primary variants: current-source converter (CSC) HVDC and voltage-source converter (VSC) HVDC. It also undertakes a comparative analysis with high-voltage alternating current (HVAC) technologies, focusing on aspects such as power transmission efficiency and cost-effectiveness, drawing upon prior research findings. Additionally, the paper underscores the critical role of circuit-breakers (CB) as essential components for controlling HVDC systems. HVDC technology plays a pivotal role in augmenting AC transmission systems, facilitating the integration of large-scale renewable energy sources, and enhancing the efficiency of expansive power grids over considerable distances. Its continued evolution and refinement are highly probable, given its indispensable role in the energy landscape.

Keywords: HVDC Circuit Breakers, Power Electronics, HVDC Transmission.

1. Introduction

High Voltage Direct Current (HVDC) power transmission systems are extensively employed in contemporary applications and are continually progressing. This technology has benefited from extensive research and development spanning several decades, with practical implementations in various power transmission domains. Initially relying on thyristors, HVDC systems have now evolved to encompass multiple fully controllable semiconductor-based systems [1].

The transmission system uses AC-DC convertors (rectifiers) to convert the AC generated into DC for a more efficient transfer, and converts DC back to AC (convertors are also called as invertors) for further usage or distribution. There are two main types of convertor configuration used: CSC and VSC. The connection between the stations can be accomplished by overhead or submarine lines, or directly together in a back-to-back topology.

2. HVDC transmission

HVDC and flexible AC transmission system (FACTS) are important technologies. There are many implementations of transmission provided by HVDC. Mainly using 2 distinct categories. It uses converters to convert AC to DC between sources and cables.

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2.1. HVDC topologies

The configuration of an HVDC transmission system varies to accommodate different requirements. There are several distinct configurations shown in Figure 1:

1. Back-to-Back Connection: This setup can be defined literally, that only one location is used to configure both the rectifier and invertor. As a result, the DC line connecting them is typically very short, spanning only a few metres.
2. Monopolar Connection: Monopolar configurations involve separating the convertors with a single DC pole line, regardless of the polarity. The ground serves as the path for current return. It can be classified as symmetric when the midpoint of the ground is between the positive and negative polarities, or asymmetric when the ground is neutral. This configuration is frequently used for submarine cable transmissions.
3. Bipolar Connection: Two independent monopolar systems with opposite polarities make up a bipolar connection. Both monopoles can operate separately, with the ground serving as the return path. It can continue transmitting power even if one of the monopoles goes out of service. When both monopoles are active with equal currents, theoretically, there should be no current in the ground. This configuration is commonly employed for power transmission via overhead DC lines.
4. Multi-terminal Connection: This configuration involves the use of three or more sets of converters that can function independently. Each set can act as either an inverter or a rectifier. Multi-terminal connections can be established in various arrangements, such as radial, mesh, ring, parallel, or series configurations [2].

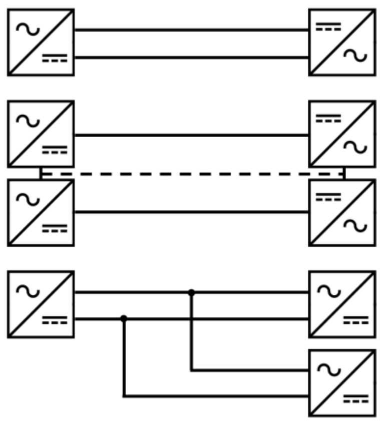

Figure 1. Circuit diagrams for long distance topologies. From top to bottom: monopolar, bipolar, multiterminal connections.

2.2. CSC-HVDC

Thyristor technologies are used as the convertors in CSC-HVDC (see Figure 2). Thyristors are semiconductor devices comprising four layers of N and P-type materials, allowing them to block the flow of signals until a control gate receives a pulse, and this state persists until another current zero-crossing [3].

Changing the firing angle on both the rectifier and inverter sides allows regulation to be finished in the CSC-HVDC system. This results in a continuous flow of constant DC current being injected into the receiving AC network. If the DC voltage polarity is reversed at both ends, the direction of power transfer between the two ends is reversed, while the current remains unchanged [3].

CSC-HVDC is particularly well-suited for transmitting large-scale power via high voltage methods. Its noteworthy attributes include robust reliability and relatively low maintenance requirements, contributing to its widespread popularity [4].

Table 1 provides several instances of projects worldwide that utilize CSC-HVDC technology. Notably, the Changji-Guquan project in China boasts the longest DC line, the highest transmitted power capacity, and DC voltage among these examples.

Table 1. Examples of projects using CSC-HVDC technology [5].

Scheme	Location	Transmit Power (MW)	DC Voltage (kV)	DC line length (km)	Year
CASA1000	Tajikistan and Pakistan	1300	±500	800	2021
Changji-Guquan	China	12000	±1100	3000	2017-2018
Jinbei-Nanjing	China	8000	±800	1118	2017
Jiuquan-Hunan	China	8000	±800	2390	2017
Oklaunion	USA	220	345	Back-to-Back	2014
Rio Madeira	Brazil	3150	±600	2500	2012
SAPEI	Italy	1000	±500	-	2011
Norned	Norway and The Netherlands	700	±450	-	2008
New Zealand Inter-Island HVDC	New Zealand	560	350	575	1991-1992
Quebac-New England	Canada and USA	2000	±450	1480	1990-1992
Inga-Kolwezi	DR Congo	560	±500	1700	1982
Cahora-Bassa	Mocambique and South Africa	1930	±533	1420	1977-1979

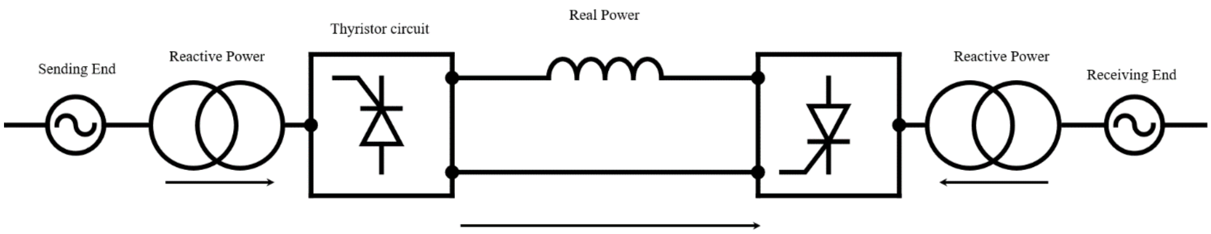

Figure 2. Circuit diagram for CSC-HVDC with thyristors.

2.3. VSC-HVDC

VSC-HVDC employs different configurations at their convertor stations. These VSC stations are composed of insulated gate bipolar transistors (IGBTs), as illustrated in Figure 3. Notably, IGBTs allow for the switching of currents on and off at any given moment. In the event of a black start scenario, VSC-HVDC systems have the capability to generate their own AC voltage [5].

These converters function through pulse width modulation (PWM), enabling the adjustment of both the phase angle and amplitude. Consequently, this technology permits independent regulation on voltage, frequency, and both active and reactive power [2].

The half-bridge VSC or two-level pole is the simplest arrangement of a VSC convertor station (Figure 4). It is consisted of two switch cells, S_1 and S_2. Each of them is composed by a unidirectional switch connected with a diode in anti-parallel. If S_1 is on and S_4 is off, there will be a voltage $\frac{V}{2}$ between the neutral point M and the AC output terminal a, where V is the DC voltage. When both of the two switches change their states, the electrical potential regarding M will be in reversed polarity, so the voltage V_{Ma} will be $-\frac{V}{2}$ [4].

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The switch gates are conducted by a set of signals, which alters its construction and connection states of the switches so as to modify the output voltage level. The gate signals are binary, in which 1 represents ON and 0 represents OFF state. It is easily noted that $s_1(t) + s_2(t) \equiv 1$, i.e., at one time only one of the two switches will be switched on. The PWM is used to control the turn ON/OFF command [4].

The two-level pole is a traditional block of all convertors. It has advantages including small footprint, small DC capacitors, simple circuits. The major drawback is that its inability to produce zero output in order to manage the output voltages' amplitude, which can be resolved by applying other techniques on the PWM [5]. Many other configurations, including full-bridge single-phase VSC, three-phase two-level VSC, are extensions of this one.

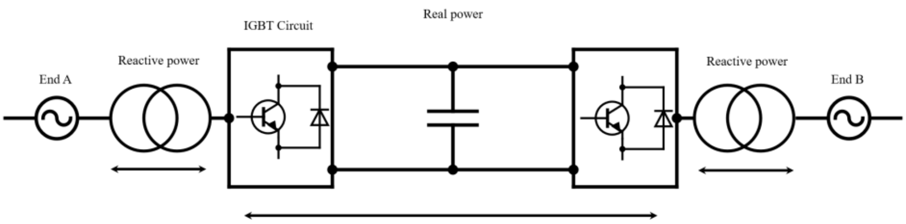

Figure 3. Circuit diagram for VSC-HVDC technology with IGBTs.

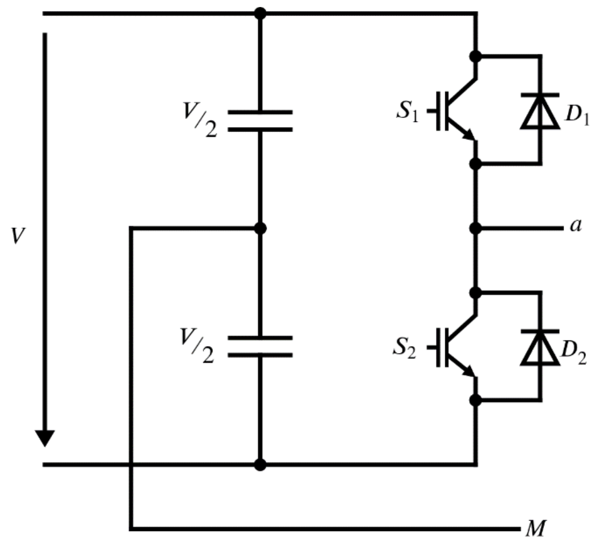

Figure 4. The configuration of a two-level pole VSC-HVDC converter.

3. Comparisons

3.1. Comparison between HVDC and HVAC technology

Generally, a DC line is more economically efficient than an AC line on long distances. A study done showed that there are more transmission costs (investment cost and loss cost) of AC than DC for a 1200-km distance transmission [6]. Additionally, the line is not fully utilised up to its thermal limits in an AC transmission because of the skin-effect (the concentration of charges is focused more near the surface), otherwise in a DC line. Also, HVAC suffers from the surge impedance load (SIL) of AC lines, for it generates and consumes reactive power during transmission, which can be estimated $0.0005V^{2.2939}$MW of power is lost via SIL (V is measured in kV) [7]. More conductors are used in AC cables, making then more expensive [2].

However, HVAC contains more advantages than HVDC when talking about substations. The installation of the convertor stations is higher than HVAC. The use of HV transformers is usually more efficient (the loss in an AC double-circuit transformer is typically around 0.3%) than the stations in HVDC (some VSC-HVDC convertor stations can have a power loss >1%) [4]. As a result, in short distances, the HVAC would better suit the transmission need, while in long distances, HVDC is more economic and is more likely to be put into use (Figure 5). It can be deferred that the HVAC technology is justified more economic before the breakeven distance plotted on the graph, and the other way round after. The difference in the y-intercept is the difference in costs of the substations.

It is also noteworthy that not in every situation that HVDC is superior in HVAC in relatively long distances. It is too precipitate to make choices on technologies simply by a cost-distance diagram. Other factors, including levels of attenuation, frequency of the interconnected stations, equipment, etc. ought to be considered [8].

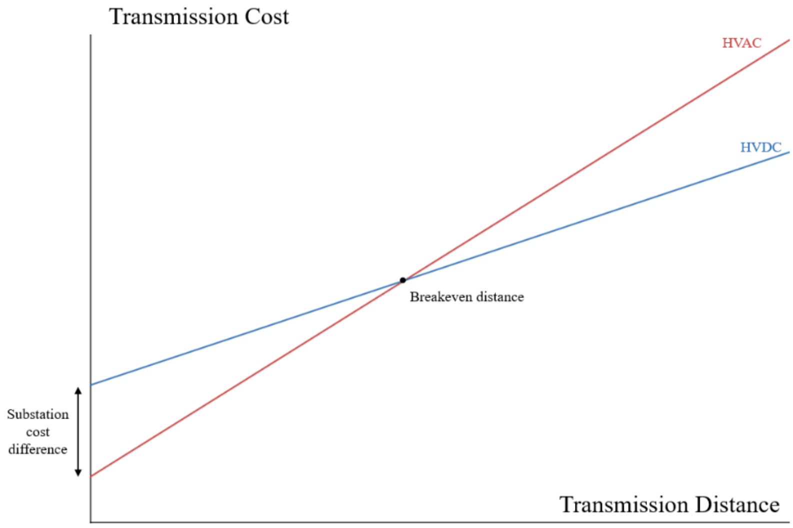

Figure 5. Total costs against transmission distance of HVAC and HVDC.

3.2. Comparison between CSC-HVDC and VSC-HVDC technologies

A study has been done to analyse the comparison in convertor buildings between CSC and VSC-HVDC by selecting similar examples. The research group chose the Grita and the EWIC project as examples of CSC and VSC technologies respectively [3]. Table 2 described their key features. It is apparent that they are similar. The results have shown that the implementation of VSC convertor requires more height and more volume. A more general comparison is listed in Table 3 [3].

Table 2. Key features of Grita and EWIC schemes [3].

Schemes	Grita	EWIC
Technology	CSC	2-Level VSC
Transmission Power (MW)	500	500
AC voltage (kV)	400	400
DC voltage (kV)	400	±200
Total line length (km)	313	261
Topology type	Asymmetric monopolar	Symmetric monopolar
Transformer Arrangement	1-phase 3-winding	1-phase 2-winding

Table 3. Comparisons between VSC and CSC.

Technology	CSC	VSC
Semiconductor	Thyristor	IGBT (Transistor)
Power control	Active	Active or reactive
Minimum short circuit ratio	>2	0
Black start capability	No	Yes

4. CBs for HVDC systems

HVDC circuit breakers (CBs) are not as developed as their HVAC transmission counterparts. These CBs exhibit effectiveness when they are interconnected in a series, requiring all of them to commutate simultaneously. Any failure to operate in this synchronized manner can lead to a CB malfunction.

Typically, an HVDC CB consists of two components connected in parallel with the main current branch, comprising the commutation branch (referred to as Branch A) and the energy dissipation branch (referred to as Branch C), along with another branch (Branch B). When a fault occurs in Branch A, the current is redirected into Branch B by injecting active current or deactivating electronic switches [9]. Subsequently, a counter voltage is built up by charging the capacitors in Branch B to suppress the fault current [9]. Once the voltage in Branch B reaches the protection levels of metal oxide surge arrestors (MOSA) in Branch C, the MOSAs dissipate inductance energy, along with energies supplied from the voltage source [9]. As the CB's current decreases to the leakage level, it remains resilient at a rated voltage until a switch interrupts the current to isolate the CB [9].

Several configurations are outlined [10]:

1. Utilising a conventional AC CB in conjunction with:

A resonance circuit in parallel.

A charged capacitor in parallel.

2. Employing a solid-state CB, which can be constructed by:

Implementing a bidirectional switch using controllable devices and diodes.

Utilising a circuit composed of switches such as IGBT, integrated gate-commutated thyristor (IGCT), gate turn-off thyristor (GTO), connected with a diode in antiparallel.

3. Combining both options 1 and 2, utilising a solid-state breaker in parallel with a conventional AC CB.

5. Conclusion

This paper gives a review of HVDC, including convertors, circuit breakers, topologies. Comparisons amongst themselves and HVAC have shown that though it weighs a lot of advantage already and its worldwide installations are competitive, especially for long distances, some technologies, such as the efficiency of the convertors and the control of the circuit still have high potential. Systems using HVDC have provided up to at least 12GW of power with a voltage as high as 1100kV at a station. It is certain that HVDC will continue to grow, and will be considered to be a solution for more power electronic problems at a higher power rating and higher voltage.

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