



VOLTAGE-SOURCED CONVERTER-BASED HVDC TRANSMISSION SYSTEMS: DESIGN AND APPLICATIONS

¹Ibrahim Muhammad Kende

Department of Electrical Engr.

Kalinga University, Naya Raipur.

²Ahmad Musa Galadima

Department of Civil Engr.

Kalinga University, Naya Raipur.

³Bala Sadiq Malami

Department of Civil Engr.

Kalinga University, Naya Raipur.

⁴Bello Bello Udulu

Department of Civil Engr.

Kalinga University, Naya Raipur.

⁵Rajendra Kumar

Department of Electrical Engr.

Kalinga University, Naya Raipur.

Abstract

Voltage-Sourced Converters (VSCs) are now much more feasible in High Voltage Direct Current (HVDC) transmission systems thanks to the quick development of power electronic devices with turn-off capabilities, such as Insulated Gate Bipolar Transistors (IGBTs) and Gate Turn-Off Thyristors (GTOs). Comparing this novel technique to traditional HVDC systems based on thyristor technology reveals significant technical and financial advantages. The use of VSC-based HVDC systems for high-power ratings (up to 200 MW), which are being considered for a number of projects, is examined in this research. Following a description of the main circuit elements, the paper offers a summary of the crucial design elements of VSC-based HVDC systems.

Keywords: Transient Stress, Insulation Coordination, Harmonic Performance, Power Electronics, HVDC, and VSC.

1. INTRODUCTION

For conventional HVDC transmission systems to function dependably, an AC network with adequate short-circuit power is necessary. Historically, costly rotating synchronous phase shifters have been utilized to guarantee steady operation in poor system conditions.

An HVDC system that uses Voltage-Sourced Converters (VSCs), on the other hand, has semiconductor components like Insulated Gate Bipolar Transistors (IGBTs) that can be controlled to turn on and off. This gives the converter control over the voltage and frequency of the AC system and allows it to operate in networks with low short-circuit power or even in passive systems without local generation.

Reactive power support, which varies based on the active power transfer, is always necessary for thyristor-based converters used in typical HVDC systems. Additional parts, like switching capacitor banks or Static Var Compensators (SVCs), are frequently needed to satisfy this demand. In this study, we call VSC-based HVDC transmission HVDC^{plus}, which stands for Power Link Universal Systems, an affordable answer to challenging power distribution and transmission problems. HVDC^{plus} salient features include:

- I. Independent Active and Reactive Power Control: Within the parameters of its overall MVA rating, each station has the ability to independently control both active and reactive power, allowing for both power transmission and AC voltage stabilization.
- II. Function in Weak or Passive AC Systems: The system is capable of supporting passive grids without local generation as well as networks with minimal short-circuit power.
- III. STATCOM Functionality: Maintains AC bus voltage and enhances system stability by offering continuously adjustable reactive power assistance.
- IV. Flexible Power Exchange: Within the station's overall power capacity, active and reactive power can be managed separately.

In applications like these, HVDC^{plus} is becoming a more sophisticated substitute for traditional HVDC systems.

- a) Multi-terminal networks of HVDC
- b) Connecting isolated or weak AC grids
- c) Connecting lower- to mid-power AC systems
- d) Delivering isolated, distant loads (such as offshore oil and gas platforms).
- e) Connecting offshore and onshore wind farms

HVDC Plus is a strong alternative to conventional thyristor-based HVDC systems because of these benefits. In the near future, it is anticipated that ongoing developments in power semiconductor technology will increase the commercial applications of VSC-based HVDC systems.

2. TRANSMISSION SYSTEMS FOR HVDC^{plus}

Currently, HVDC^{plus} systems with power ratings of up to 200 MW per 12-pulse bipolar unit are available. These systems function at DC currents exceeding 700 A and DC voltages up to ± 150 kV. A typical HVDC^{plus} transmission scheme is shown in Figure 1, which consists of two converter stations, Station A and Station B, connected by an overhead line or a DC cable. The following are the system's main power components:

- a) Voltage-Sourced Converters (VSCs)
- b) High Voltage DC Circuit
- c) Transformers

Figure 1 depicts a bipolar layout of the system. Two identical VSCs that individually produce a DC voltage V_{dc} make up each station. To stop ground current flow, one station is grounded using a grounding impedance and a Zinc Oxide (ZnO) arrester connected in parallel, while the other station is grounded using just an arrester.

HVDC^{plus} schemes can be constructed as back-to-back stations or as monopolar systems, just as traditional HVDC systems. A more thorough explanation of the main power components is given in the sections that follow.

2.1 DC Circuit with High Voltage

Storage capacitors and the transmission medium, which may be an overhead line or a DC cable, make up the DC circuit. The VSC runs on a steady DC voltage with fixed polarity thanks to storage capacitors. The capacitors must be linked with the least amount of inductance possible in order to optimize the power semiconductors' efficiency in the VSC. The permitted DC voltage ripple is used to calculate their size.

The stable polarity of the DC voltage is a major benefit of HVDC^{plus} technology. Power reversal in traditional thyristor-based HVDC systems necessitates altering the polarity of the DC voltage, which produces transient effects that call for stronger insulation and unique DC cable design. On the other hand, HVDC^{plus} systems do not require polarity reversal; instead, power reversal is accomplished by merely reversing the direction of the DC current. This makes it possible to employ sophisticated extruded DC cables, which are more flexible and affordable than conventional mass-impregnated or oil-filled paper-insulated cables.

For long-distance power transfer, HVDC^{plus} transmission is a good substitute for AC transmission systems, where cable length is constrained by the need for reactive power compensation. The large capacitive charging current in AC cable transmission can significantly reduce system performance. This restriction does not affect HVDC^{plus} transmission, which makes

it ideal for long-distance subterranean or submarine cable applications.

The DC capacitors of the interconnected VSCs can be directly connected in parallel for HVDC^{plus} systems set up as back-to-back stations, which further streamline the system design.

2.2 HVDC^{plus} Voltage-Sourced Converters

Based on how they work, converters in power systems can be roughly divided into two groups. To function, the first kind, known as Line-Commutated Converters (LCCs), needs an external AC power supply. Thyristors regulate the switching points of these converters, which use the AC system voltage to drive current to commute between phases. LCC technology is the foundation of traditional HVDC systems. Self-Commutated Converters,

the second group, function without the assistance of an AC system. Voltage-Sourced Converters (VSCs) and Current Source Converters (CSCs) are subcategories of this group. A VSC uses a storage capacitor to generate a steady DC voltage, whereas a CSC uses a reactor to maintain a steady DC current.

In industrial settings, VSC technology has long been used, especially in motor drives. Advances in power semiconductor technology and its successful integration in Flexible AC Transmission Systems (FACTS) devices, like the 320 MVA Unified Power Flow Controller (UPFC) and the ± 100 Mvar SVC Statcom, have fueled its acceptance in high-voltage applications. These systems have shown how VSCs can improve power system control and stability.

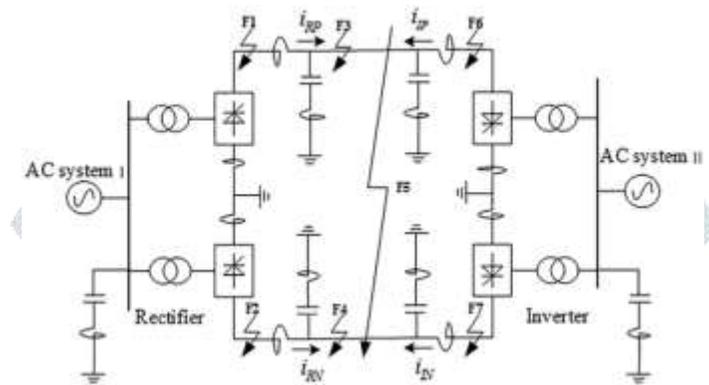


Fig. 1: Main Circuit Diagram of a Bipolar HVDC+ Transmission System

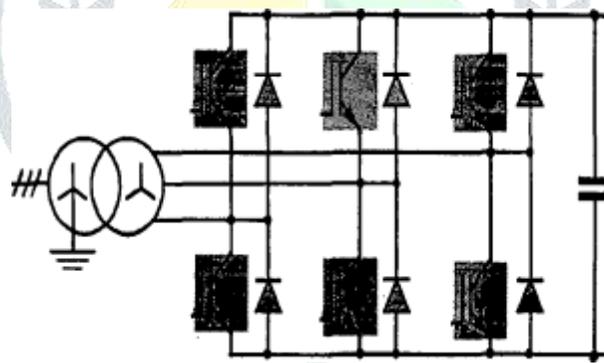


Fig. 2: Equivalent Circuit of a 2-Level IGBT-Based Converter

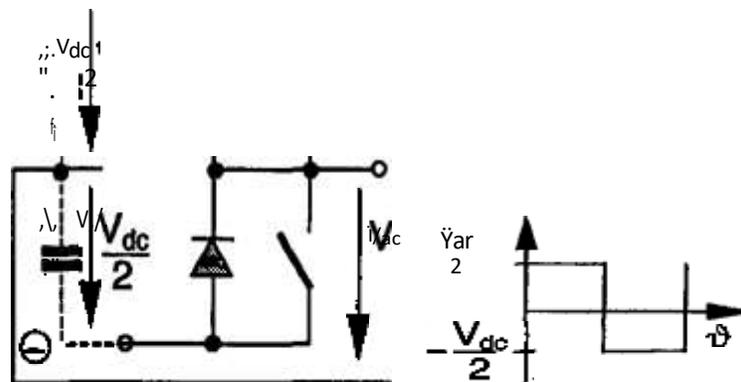


Fig. 3: Fundamental Operating Principle of a 2-Level VSC

HVDC^{plus} systems have been developed as a result of the integration of VSC technology with HVDC transmission. The analogous circuit of a VSC utilized in HVDC^{plus} transmission is shown in Figure 2. An anti-parallel linked six-pulse bridge of freewheeling diodes and a six-pulse bridge of Insulated Gate Bipolar Transistors (IGBTs) make up the VSC. IGBTs are favored because of their capacity to manage greater DC voltages, but both IGBTs and Gate Turn-Off Thyristors (GTOs) can be utilized as switching devices. Higher DC voltages are beneficial for lowering transmission losses in long-distance HVDC^{plus} transmission. Present-day IGBT technology has a power rating of about 140 MVA per converter and can block voltages up to 150 kV. A single VSC can carry up to 800 A (RMS) of AC line current.

Fundamental Functions of a VSC

A VSC's primary job is to transform the DC voltage that is kept in capacitors into regulated AC voltages. A two-level VSC's basic operation is depicted in Figure 3. IGBTs are turned on and off by means of gate signals, whilst the diode rectifier determines the polarity of the DC voltage. One IGBT in a phase leg must always be turned off before the other is turned on in order to avoid a capacitor short circuit.

A stepped waveform is created when the AC terminal voltage alternates between $+V_{dc}/2$ and $-V_{dc}/2$ due to the alternating switching of IGBTs in each phase. The high switching frequency, which is significantly higher than the frequency of the AC system, makes it possible to create a sinusoidal output current using Pulse Width Modulation (PWM) techniques.

Three-Level Converters Powered by Voltage

Three-level VSCs outperform two-level converters in terms of harmonic performance for higher power applications. An analogous schematic of a three-level VSC is shown in Figure 4. Figure 5 illustrates this arrangement, which has four valves per phase leg. Only two neighboring valves (such as S1 and S2, S2 and S3, or S3 and S4) may be switched on at the same time, according to the switching rule.

S1 and S2 are turned on, and the AC terminal is linked to $+V_{dc}/2$.

S2 and S3 ON \rightarrow 0V is connected to the AC terminal (midpoint tapping)

$-V_{dc}/2$ is connected to the S3 and S4 ON \rightarrow AC terminal.

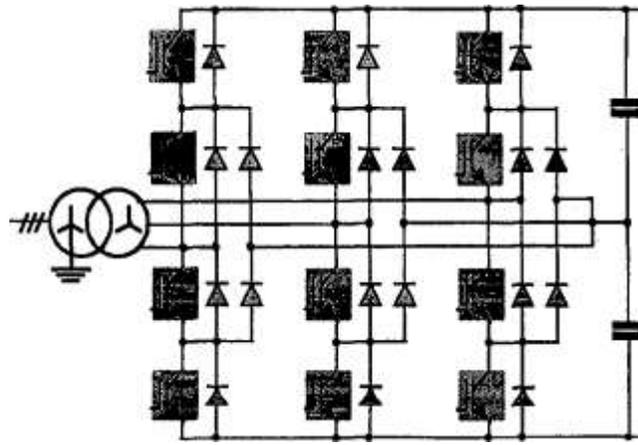


Fig. 4: Equivalent Circuit of a 3-Level IGBT-Based VSC

Instead of the two-level output of simpler VSCs, this produces an AC voltage waveform with three distinct levels. Three-level VSCs require a larger footprint and higher investment expenses, despite the fact that they greatly reduce harmonic distortion. Because of this, two-level VSC technology is still the best option for HVDC^{plus} applications.

2.3 Transformers

Transformers are used to connect the converters to the AC network in the majority of HVDC^{plus} transmission systems. These transformers carry out a number of vital tasks:

- Providing Reactance:** To reduce fault currents and enhance system stability, they add reactance between the converter's AC terminals and the AC system.
- Voltage matching** is the process of increasing or decreasing the AC system voltage to levels that are best suited for the voltage and current ratings of the converter.
- Phase-shifting for 12-Pulse Converters:** They reduce harmonic distortion by enabling the coupling of two six-pulse converters to create a 12-pulse group.
- Potential Isolation:** By allowing two converters with dissimilar DC potentials to be connected to ground, they guarantee appropriate electrical isolation.

However, functionalities 2, 3, and 4 might not be required in some HVDC^{plus} system designs. A reactor coil can take the place of the transformer if the AC system voltage already satisfies the converter's voltage and current requirements and just one converter per station is needed. Both complexity and installation expenses are decreased by this streamlined design.

Effects of the Converter Turning on reactors and transformers

Rectangular AC voltage waveforms produced by the converter are presented to transformers or reactors in HVDC^{plus} systems (Fig. 3). A two-level VSC produces sharp voltage steps (high dv/dt) as a result of the phase voltage's quick transition from zero to V_{dc} in microseconds. Transformer insulating materials are subjected to severe electrical strains as a result of these quick fluctuations, which could shorten the equipment's lifespan.

Low-pass filters can be added at the converter's AC terminals to lessen these impacts. By lowering dv/dt values, these filters lessen insulation stress and help create a converter station that is more dependable and cost-effective.

3. ASPECTS OF DESIGN

3.1 Features of the Steady-State

A simplified single-line diagram for examining the basic load flow between an AC system and an HVDC+ Voltage-Sourced Converter (VSC) is shown in Fig. 6. A transformer with an ideal transformation ratio and corresponding leakage impedance (X_l) connects the AC system and the VSC, which are both represented in this representation as voltage sources.

The power flow conditions of the AC system dictate the magnitude and phase angle of the AC system voltage (V_n), whereas converter control allows for the adjustment of the converter's voltage (V_c). Kirchhoff's Voltage Law states that controlling V_c in relation to V_n causes a voltage drop across the transformer's leakage reactance, X_l , that is proportional. The electrical current I through X_l lag by 90° when losses are ignored. Thus, direct control of the current I passing through the system is made possible by varying V_c .

The relationship between voltages and currents under particular operating conditions is shown in Fig. 7. In relation to V_n , the current I can be broken down into two parts:

In phase with V_n , the parallel component controls the exchange of active power (P). Reactive power (Q) exchange is controlled by the quadrature component (90° phase shift from V_n). At the transformer's AC system side, the exchange of active and reactive power is determined by:

$$P_N = \frac{V_N \cdot V_{conv}}{X_T} \cdot \sin(\delta)$$

$$Q_N = \frac{V_N}{X_T} (V_N - V_{conv} \cos(\delta))$$

where:

V_n : Current AC system voltage magnitude

V_n, nom : The nominal voltage of the AC system

V_{conv} : The current converter AC voltage magnitude

P_n : Power exchange that is active at the AC system terminals

Q_n : Exchange of reactive power at the terminals of the AC system

S_t : The transformers rated apparent power

By using suitable converter control strategies, the operational range of an HVDC station in terms of active and reactive power can be optimized for a given AC system voltage V_n .

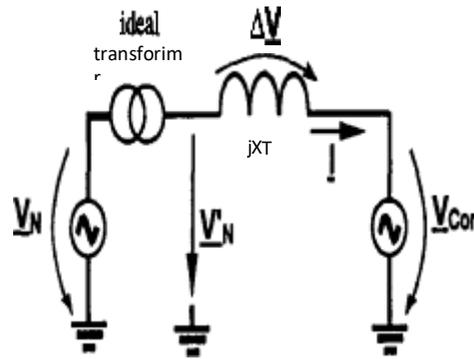


Fig. 5: Equivalent Circuit for Fundamental Load Flow Calculation Between VSC and AC System.

Harmonics and Power Control in VSC-HVDC Systems

The operating points produce straight lines by keeping α constant while altering V_c , as shown for V_c and G . On the other hand, concentric circles are produced by altering α while maintaining V_c constant, as demonstrated for AN , $k = 1.0$, $k = 1.0$, and L .

The symbol for the station's power rating is the circle $|P_N + jQ_N| = 1.0$ pu, which is equal to $|PN + jQN| = 1.0$. The VSC can function continuously at any point in this circle by varying V_c and V_s , allowing for independent control of the interchange of active and reactive power. The station can operate as a STATCOM, supporting the linked AC system with either capacitive or inductive reactive power, even when active power transfer is not present.

3.2 Harmonics

VSCs produce harmonic voltages and currents in both AC and DC systems, much like any other power electronic converter. A VSC acts as a harmonic voltage source behind the transformer impedance when viewed from the standpoint of the AC system. It works in parallel with the storage capacitor as a harmonic current source on the DC side. Compared to traditional line-commutated converters, this behavior is different.

The degree of harmonic production is determined by:

The topology of the converter for instance, a 6-pulse Vs a 12-pulse design

The used pulse pattern

The frequency of switching

Both the AC and DC sides' harmonic performance is enhanced by a 12-pulse design, with distinctive AC harmonics that follow the following sequence:

$$v_A = 12n \pm 1, n = 1, 2, \dots$$

and characteristic DC harmonics following:

$$v_D = 12n, n=1,2,\dots$$

In a perfect world, all other harmonics are eliminated.

Harmonic production is lessened by higher switching frequency. Simple Pulse Width Modulation (PWM) techniques, such as delta-sinus modulation, are possible at frequencies in the kilohertz region. Harmonics at multiples of the switching frequency are usually the outcome of this method. Nevertheless, higher converter losses brought on by higher switching frequencies not only lower the available transmitted power but also put more heat strain on power electronics, which may have an impact on overall efficiency.

By using optimized pulse patterns, advanced PWM approaches can assist reduce certain harmonics and enable lower switching frequencies without sacrificing acceptable harmonic performance.

VSC-HVDC Systems: Harmonic Performance and Insulation Coordination

3.2 Harmonic Performance

A VSC-HVDC transmission scheme's optimization must strike a compromise between operating losses, switching frequency, pulse patterns, and harmonic performance requirements. In order to achieve dependable and effective system performance, several elements are essential. Compared to traditional line-commutated converters, VSC technology has substantially less harmonic interference because of its built-in harmonic removal capacity. Additional harmonic filtering on both the AC and DC sides, however, can be necessary based on system-specific considerations such loss evaluations, AC system harmonic impedance, DC line or cable impedance, and harmonic performance requirements.

3.3 Coordination of Insulation

Surge arresters are positioned strategically on both the AC and DC sides of HVDC power components to guard against transient overvoltage's brought on by switching surges and lightning strikes.

a) Arresters on the AC side:

AC filter arrester (if applicable)

AC bus arrester

b) Arresters on the DC side:

DC line arresters

DC filter arrester (if applicable)

Neutral bus arrester

The maximum voltage levels experienced during continuous operation are used to determine the Maximum Continuous Operating Voltage (MCOV) for arresters. An extra margin is included to accommodate for measurement tolerances and transient situations.

Arrester ratings are established by examining a variety of fault scenarios to make sure the insulation is strong enough to withstand switching surges and lightning strikes. Each component's withstand values are established using standard HVDC procedures and specified by IEC 60071-5.

4. Short-Term Stresses

A variety of fault scenarios can cause transient voltage and current strains to affect components of an HVDC^{plus} system, just like they can any other equipment in power systems. These breakdowns fall into two groups: internal (occurring within the transmission system itself) and external (occurring outside the transmission system, within the AC network).

The design objective for external faults is to give the malfunctioning AC system the best possible support in addition to safeguarding the equipment. The system can help by offering dynamic voltage control and damping power oscillations following voltage recovery, depending on the fault clearance technique. The HVDC^{plus} system is especially good at responding to these kinds of problems because of its quick reactive power control capability and its capacity to either provide or absorb active power. The goal is to minimize internal problems by ensuring a secure station layout and adequate design margins for every component. To reduce damage and guarantee system stability, quick protective systems are in place for all components in the event of an internal problem.

5. Overview

Advanced technology in high-power transmission and distribution is referred to as HVDC^{plus}. High DC voltages of up to 150 kV per VSC and AC currents of up to 800 A are made possible by the novel Voltage Source Converters (VSC), which make it possible to create a 150 kV bipolar transmission system with power ratings of up to 200 MW at a very low cost.

In addition to transmitting active electricity across systems, an HVDC^{plus} system also integrates STATCOM capability. The only restriction on the system's ability to independently control reactive power exchange with the AC systems is the station's power rating. Because of this flexibility, thyristor-controlled converters don't require the additional investment in capacitor banks or SVCs that would be necessary in traditional HVDC systems to offset their reactive power requirement.

By combining the high-power switching power of GTOs (Gate Turn-Off Thyristors) with the voltage and current controllability of a transistor in both the on and off states, the VSCs are outfitted with contemporary IGBTs (Insulated-Gate Bipolar Transistors). This combination produces a strong converter design, which adds to the transmission system's high overall reliability. Significant technical benefits are provided by the HVDC^{plus} transmission system, particularly for applications involving the connection of extremely weak AC systems in the lower to mid-power range, whether in point-to-point or multi-terminal designs.

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