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A Technical Review on High Voltage Direct Current (HVDC) Transmission

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Abstract

This paper reviews the High Voltage Direct Current (HVDC) transmission technology and presents a systematic analysis of recent developments in the technology as well as the opportunities that the technology can exploit to enhance transmission efficiency. It also discusses challenges in the widespread acceptance of the technology as a means of transmission and ways to mitigate them. It further incorporates a brief overview on the underlying technology of HVDC system.

Keywords - HVDC, LCC, PWM, SCADA, Smart-grid, VSC

I. INTRODUCTION

Direct Current (DC), since the early history of the electrical power industry, has remained as the key technology for the generation and transmission of electrical power for many years [1]. As the need to transmit large power over long distances grew over time, Alternating Current (AC) transmission systems started replacing DC power transmission systems because the low power handling capacity of DC system cannot allow transmission of large power over long distances [2]. Due to the power handling limitation of traditional electronic devices, boosting the level of DC voltage was not possible, which restricted its use for large power transmission [3]. Recently, the advent of power electronic devices that are capable of handling a large amount of power and high-frequency switching has made the conversion and transmission of high power electrical energy in the form of (voltage elevated) DC a reality. The high voltage DC technology, commonly known as the HVDC (High Voltage Direct Current), has addressed the issue of low power handling capacity of DC systems through elevated voltage level [4]. The development of High Voltage Direct Current (HVDC) system is solely based on the growth of power semiconductor devices that offers features like high-voltage and high-power handling capacity along with full controllability. Recent development has made transmission of 3-4 GW electrical power over long distances possible by just one bipolar line using HVDC system [5]. Since the first commercial transmission of HVDC in Sweden in 1954, the technology had never ceased to show its potential to become an alternative choice for electrical power transmission because of its better performance, operational simplicity, environmental benefits, power flow control, stability and ease of maintenance [6]. The design and sustainability of high-power, low-loss, and fully controlled modern electrical system depend largely on successful integration and development of HVDC technology [7].

II. AN OVERVIEW OF HVDC TECHNOLOGY

The basic operating principle of an HVDC system is to convert AC into DC at the transmitting end and converting it back to AC from DC at the receiving end [8]. Conversion of AC to DC is done by rectifier and DC to AC is done by Inverter. HVDC converter, a bidirectional device, can perform both rectification and inversion, which makes the system simpler. In a one-way power transmission system, a converter either operates as a rectifier in the transmitting end or as an inverter in the receiving end whereas in a bidirectional power flow system like in cross-border power trading, a single converter can operate both as a rectifier and an inverter based on the direction of power flow. An HVDC converter station, similar to a substation in AC transmission system, contains all necessary terminal devices including switchgears, converters, and transformers to facilitate AC-to-DC and DC-to-AC conversion [9].

The power carrying capacity of an HVDC system is as large as its converters can handle. Converters in HVDC reduce harmonics, increase reliability and enhance fault tolerance of the transmission system [8]. Two basic type of converters play major roles in HVDC systems–Line Commutated Converters (LCC) or Current Source Converters (CSC) and Voltage Source Converters (VSC)–which are designed to exploit the advances in power electronic devices, mostly the thyristor and transistor. A control system sits between the two ends of an HVDC network, which controls the flow of active power and operation of converters in a way that the entire HVDC scheme remains independent of the magnitude, phase angle, and frequency of AC voltage.

A. LCC-HVDC

The most attractive feature of the LCC-HVDC technology is that it can operate reliably with minimal maintenance for a long period of time and is suitable for bulk power transmission. However, the line commutation technique depends on a very high synchronous voltage to make it commutating, which limits the use of LCC in black start operation [3].

The LCC-HVDC uses thyristor-based power electronic devices for the converters [8]. These devices are switched on by an external pulse and off naturally by the zero-crossing current in the circuit. One serious limitation of LCC is that it can control the active power but not the reactive power. When the voltage across the thyristor switch is forward biased, the gate pulse fires the device and makes it conducting. When the current crosses zero, the device becomes non-conducting due to the applied reverse bias

[4]. Thus, current can conduct in one direction only. During the commutation process, an LCC converter generates a substantial number of harmonics, which necessitates the system to incorporate a large number of AC harmonic filters along with reactive power control units; consequently, the required space area is larger; about ten times more space is required to accommodate an LCC-HVDC system compared to an AC substation of similar capacity [10]. Nevertheless, its operational efficiency is much higher than that of an equivalent AC system. Besides high availability of around 98-99%, an LCC-HVDC can achieve about 98% efficiency including all losses at terminals but excluding the transmission losses [10].

LCC has the largest market share in the HVDC industry because it uses well-established, more reliable and fault-tolerant thyristor-based technology and offers the highest power rating among HVDC converters [8]. Being the oldest HVDC technology, it is sometimes referred to as "classic" HVDC [7]. However, these systems are being replaced largely by newly introduced VSC-HVDC system, which has the potential to become next generation HVDC technology.

B. VSC-HVDC

The VSC-HVDC system successfully resolves many conventional network issues like interconnection of asynchronous networks, back-to-back linking of AC systems and maintaining voltage stability over small and long distances. It further supports large-scale renewable energy integration to the grids, which makes it a preferable choice for future grid system [7]. However, it has few capacity limits compared to the LCC-HVDC system due to having low device rating, higher dielectric stresses on the insulation of equipment and higher power losses [8]. These limitations are caused by the high operating frequency.

VSC converters use Insulated Gate Bipolar Transistor (IGBT) switches to convert DC voltage into AC. The switches are switched on and off many times, usually at a frequency of 1kHz, during each power frequency cycle, which enables them to eliminate lower order harmonics and makes the rating of filter lower than that of LCC-HVDC [10]. The most prolific advantage of a VSC-HVDC comes from its controllability; unlike LCC-HVDC system, it can control both active and reactive power flow through the control of phase angle and magnitude of the voltage created by the converter [11]. Reactive power controllability adds to its ability to produce low harmonic output, which eliminates the necessity to use harmonic filters. Consequently, the space requirement for these VSC-HVDC converter station reduces to 60%-75% of that of an LCC-HVDC system [12]. Moreover, reactive power controllability gives control over voltage and makes the reactive power flow at one terminal independent of the other [13]. Due to less power handling capacity as compared to "classic" HVDC, it is sometimes referred to as HVDC "light" [14].

III. RECENT DEVELOPMENT IN HVDC TECHNOLOGY

Recent development in the field of Power electronics and discoveries in power transmission technologies have made the HVDC technology more competent for the transmission of electrical power and integration with the AC systems. For example, the invention of 3-level natural point clamped VSC converters allows the generation of one or more DC voltage levels that can be used to reconstruct sinusoidal shapes of AC voltage more precisely [10]. This contributes to the reduction of harmonics to lower levels. Many types of research are ongoing to find ways to reduce the capacity limitations inherent to the VSC-HVDC system such as low device rating, high losses; recently, its application has recorded 1800 MW of power transmission at 500 KV [8]. The never-ceasing research and development in the field of converter design and HVDC technology are likely to exploit the advantages of VSC-HVDC converters that offer flexibility and control at the same time.

Recent development has seen a current rating up to 6250 A and a blocking voltage level up to 10 kV, which has made LCC a preferable converter for very high voltage applications [15]. The convertor station loss of HVDC system has been reduced from 3% to 1% in recent years. [16]. The Zhundong-Sichuan Project in China has successfully transmitted 10,000 MW of electrical power using 1100 kV voltage level to a distance of 2,600 km long [3].

About 75 GW of HVDC transmission capacities have been installed worldwide in about 100 HVDC projects, which is about 1.5% of the total installed generation capacity of the world [14]. An additional 48 GW is likely to be added by China by 2020 [5]. It is theoretically possible to transmit power over distances of 1000 to 2000 km by the use of HVDC system, which is about 100 times larger than the maximum continuous power transmission capacity of HVAC system. Transmission length of 300 km at a power level of 600 –800 MW has already been running using submarine cable and 1300 km length is under planning [5].

The development of multilevel VSC converters tends to reduce the capacity limitations of the technology and thereby span the gap between LCC and VSC in terms of operations and constructions. A 99.3% efficiency for LCC-HVDC and 98.2% efficiency for VSC-HVDC system have been achieved recently. Researchers all over the world are trying to improve the technical issues with VSC based HVDC system to adopt it as the prime HVDC technology for future grid system and power transmission.

IV. OPPORTUNITIES

A large percentage of world’s transmission system uses AC current because of its many technical advantages including the simplicity in the generation and use as well as relatively lower cost of devices. However, it is not the best option for many technical difficulties and economic shortfalls. Specially, in the case of interconnection of asynchronous networks and synchronization of different fundamental frequency, AC transmission system poses several technical difficulties. Particularly, AC transmission system is not a good option for long distance transmission where system loss becomes a major issue. Considering these problems, HVDC offers great opportunity to solve high-level electrical energy transmission difficulties. With the newer HVDC light technology that makes use of VSC converters and extruded DC cables with a voltage level up to 320 kV, it is possible to transmit 1200 MW of electrical power without incurring significant loss [17]. The extruded cables have the capability to keep the voltage polarity unchanged regardless of the change in the direction of power flow; the direction of the power flow is changed by changing the direction of the current flow [16]. The VSC-HVDC system facilitated by extruded cable can be used to design multiterminal systems in a relatively simple way; this makes configuration of a complete DC network with branches and ring structures [18]. Feeding islands and distant communities is feasible with HVDC technology, which will facilitate inhabitants in remote places and help in the reduction of inhabitation problem [19].

HVDC finds its application in undersea power transmission as well as in short distance power transmission also. It also supports underground cabling, which ensures aesthetic beauty, space utilization and reduced risk of electrical or fire hazards. The HVDC links are equipped with communication links that offer centralized control and monitoring of entire grid system. The system has the capability to be integrated with the SCADA system; a minimal number of operators is required to ensure continuous and smooth operation [13].

HVDC technology is less harmful to the health and environment since unlike AC, it does not have a low-frequency oscillating field that creates a magnetic field. The static magnetic field created by HVDC is less than earth's magnetic field and does not have a significant impact on health [10]. Rapid active power controllability of HVDC system helps it in keeping power swing within the safe limit and thereby mitigating system faults considerably [10].

The integration of a large amount of renewable energy to the grid system can greatly be facilitated by HVDC system [20] [21]. For example, the wind and solar energy resources for electricity generation are located mostly in the remote areas from the major load centers. These sources supply a variable amount of energy that might put an additional stress on the existing HVAC transmission network with an additional concern of having a large amount of transmission power loss. Conventional long-distance AC transmission networks are designed with a reasonably certain generation and development plan whereas renewable energy sources have a higher degree of uncertainty in terms of location, technology, and amount [22]. HVDC can be a great solution to interconnect national grid system to remotely located renewable energy sources without the loss of integrity or concern for power loss [10]. The concept of smart-grid that is capable of interconnecting various types of energy sources and distribution network is based on the VSC-HVDC system [22]. Economical transmission of large hydropower from long distances is also viable through HVDC; for example, about 6300 MW hydropower transmission capacity is installed in Itaipu, Brazil for transmitting power to a distance of 800 km using HVDC [6].

HVDC system is a better option for trading electrical power between two independent grids as it can handle bulk power more easily and change the direction of power flow without much difficulty. A direct link HVDC is installed between Queensland and New South Wales of Australia to facilitate electrical power trading between the independent grids of these two states [23].

A 100% increase in transmission capacity can be achieved through the conversion of the operation of HVAC into HVDC [24]. The overall cost of implementation HVDC system goes on decreasing with distance at a much higher rate than equivalent HVAC system.

V. CHALLENGES

An HVDC system occupies much larger area than equivalent HVAC system because of the large size of reactive power banks, AC switch-gears and harmonic filters [10]. Solving space requirement is a challenging issue to implement HVDC systems.

The market for HVDC being relatively small, not all manufacturers have sufficient resources and capability to produce HVDC components, which increases the unavailability and cost of HVDC components and hence poses restriction to the widespread implementation of the system [10].

Reduction of high conversion loss and harmonics generation are two technical challenges in HVDC; the conversion power loss is compensated by the lower transmission loss compared to that of HVAC. Harmonics issue is relatively lower in VSC-HVDC system compared to that of the LCC-HVDC system but the technology still is at its infant stage and has its own issues.

As opposed to the thyristor-based LCC system, VSC system requires higher frequency PWM waveforms for its efficient operation but the generation of high frequency waveforms is limited by the operating temperature, losses and the capacity of the heat sink. For greater adoption of VSC application, it is essential to deal with the issues of operating frequency and temperature [7].

The overall HVDC system is complex, which calls for trained and skilled personnel for fault detection, troubleshooting, and maintenance. Unlike LCC-HVDC, VSC-HVDC can provide black-start capability but this feature is not available unless the two converter stations are located in different grids. Although VSC-HVDC is known for voltage stability that is contributed by its ability of controlling active and reactive power very fast, a large amount of power control in very short time (typically 100 ms) can give rise to system instabilities and faults [13].

Despite the opportunity and capability to handle modern power systems, HVDC systems are fully or partially deregulated in many countries like India, China, South America and the Middle-East [25] [26] [27] [28] [29]. In order to streamline the growth of the industry and exploit the advantages offered by the technology, government regulation and infrastructural development are essential in these countries [30].

VI. CONCLUSION

This paper reviews the HVDC system from its technical aspects, the opportunities it offers and the challenges that the widespread implementation of the technology face. It discusses many recent developments that the technology has seen to focus on its prospect in becoming a preferable choice for future transmission network. It further reviews the underlying operation of the two dominant HVDC technologies.

HVDC has the potential to meet many requirements of future grid system and transmission network owing to its high transmission efficiency, lower loss and greater integrability. The technology is rapidly developing and resolving many technical difficulties that conventional transmission system fails to solve. The need for widespread and remote transmission of electrical power necessitates the development of a transmission technology that is capable of handling large power over long distances reliably and in a less troublesome manner; considering these demands, HVDC can be the transmission technology of future. The two dominant HVDC technologies, LCC and VSC, offer distinct benefits that can be utilized over a large variety of transmission networks with varying degree of technical requirements. Currently, LCC has the largest market share but VSC-HVDC system is bound to grow and achieve constant market growth in the renewable energy dominant power world of the future that is likely to integrate large-scale renewable energy to the traditional AC power grids.

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