HVDC Technology: Review and Prospect

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Abstract—The HVDC technology has significant advantages in long-distance power transmission and interconnecting different power grids to increase reliability. It has been intensively studied since its first industrial application in 1954, and it is still undergoing rapid development. In this paper, we analyzed the HVDC technology in six aspects: its history and basic theories, state-of-the art products, technical impacts, R&D challenges, real world applications, and recent related research. The aim of this paper is to provide an integrated and multi-angle retrospect and also a prospect for the HVDC technology.

Index Terms—HVDC; technology review

I. INTRODUCTION

HVDC has sixty years of commercial operation experience since the world’s first HVDC project was completed in Sweden. Due to the technology development in related areas such as power electronics, control theory, communication, and material science, the performance of HVDC has continuously been improved. Since it has significant technical advantages, HVDC is predicted to be more widely applied in future power systems.

In this paper, we conducted a multi-angle analyzes on the HVDC technology. The rest of this paper is organized as follows: Section II reviews the history of HVDC and its basic theory. Section III presents its state-of-the-art design, particularly on HVDC breakers and thyristor valves. Section IV analyzes the technical pros and cons of HVDC. The challenges in its R&D are provided in Section V. Typical applications of HVDC are listed in Section VI. Section VII shows some current related research on HVDC, and Section VIII gives the conclusions.

II. HISTORY AND BASIC THEORY

A. History of HVDC

The first long distance DC transmission was demonstrated at Munich Power Transmission in 1882 and carried 1.5KW of power. The earliest method of transmitting high-voltage direct current (HVDC) was invented by Rene Thury [1]. His electro-mechanical system (Thury system) used multiple motor-generator sets to create a high voltage output with a constant current. His system produced 630MW at 14KV DC over 75 miles. Fifteen Thury systems were in use by 1913, but required lots of maintenance due to high energy and rotary loss due to the motor-generators [1].

The development of high-voltage direct current for transmission began in the mid-1920s. The first commercial HVDC link was designed and installed in 1954 by ASEA (now known as ABB) [2]. It carried power between the mainland of Sweden and the island of Gotland. It transferred 20MW at 100KV over a 60 mile underwater cable. At this transmission length, it was ideal to use HVDC for economical and efficiency reasons. In 1970, the transmission capacity was re-engineered to support 30MW at 150KV. Soon, there were two more links added to the system that transferred 130MW at 150KV each to the island of Gotland [2]. The Sweden-Gotland link was the first of many HVDC systems. Today, there are over 100 HVDC systems around the world.

In the past, mercury-arc rectifiers were used to convert AC into DC. Mercury-arc rectifiers (also known as mercury-arc valves) are cold cathode gas-filled tubes that use a pool of mercury to carry high current. The use of mercury was an efficient way of rectifying high voltage, since it’s in a liquid form, it is self-restoring [3]. As a result, mercury arc valves were much more rugged and long lasting than other gas discharge tubes. Mercury-arc rectifiers were used up until the late 1970s when silicon technology had a breakthrough.

Thyristors use solid-state technology to rectify an AC voltage to a DC voltage. Thyristors valves quickly took over the HVDC market and made mercury-arc rectifiers obsolete. Thyristor valves are still used today and are increasingly becoming better efficient with solid-state technology breakthroughs.

B. Basic Theory of HVDC

When energy is generated, it is usually in the form of alternating voltage that carries an alternating current (AC). To transmit via DC, the voltage has to be converted from an alternating voltage to a direct voltage by a rectification process (mercury-arc rectifiers or thyristors). Once the energy is converted into DC, it must be transmitted from one place to another over transmission cables. Once the DC energy arrives at its destination, it must be converted back to AC using the same technique as before. Conventionally, the conversion process from AC to DC is called rectification. Alternatively, when DC is converted back to AC, it is called inversion. [4] Once the power is in an AC form, it is directed into the distribution system (see Fig. 1 below). An advantage of such
design allows engineers to connect two different systems with two different frequencies.

![Figure 1. HVDC Block Flow Diagram](image1)

III. STATE OF THE ART PRODUCTS

A. Hybrid HVDC Breakers

One of the most daunting tasks in creating a DC grid is having the ability to operate in the same manner that is known to AC grid operators. For the most part, DC grids are much simpler than AC because there is no frequency associated with it, and therefore no reactive power flow to worry about. Where DC grids differ, however, typically is found in the scalability, complexity and expense of their equipment. One such example is in HVDC breakers. HVDC breakers are an example of a problem that has issues with scaling. Breakers work creating a gap large enough that current can no longer flow between two contact points. The breaker can be assisted by gases or oils to make the open distance smaller than if it were in air. For example, Sulfur Hexafluoride gas works by absorbing free electrons that exist in electrical arcs and helps to extinguish current. At 2.5 times the dielectric strength of air, it make a great substitute. [5]

Unfortunately for HVDC breakers, one the main property that AC breakers rely on is the zero crossing that AC current has every cycle. Because AC current is at zero sixty times a second, even a reasonably large amount of fault current can be interrupted with a properly-sized breaker that utilizes only an air gap and a spring. HVDC breakers cannot take advantage of this property and must open ten to twenty times faster than an AC breaker [6] and may additionally need a larger gap between contacts to prevent restriking an arc.

This is where the Hybrid HVDC breaker comes in. HVDC breakers employ new ideas into breakers that eliminate the issue with scaling traditional breakers to work to interrupt DC current. HVDC breakers incorporate a traditional breaker scheme using an UFD, or Ultra-Fast Disconnector, as well as what the UFD ultimately relies on: the Insulated Gate Bipolar Transistors or IGBTs. These IGBTs act as rapid switches and serve to direct current to certain parts of the breaker. Current arresters which serve to absorb and sometimes break current. The incorporation of a current-limiting reactor is should also be noted. In DC scenarios, an inductor simply acts as a short circuit, meaning it has little effect on this line other than providing some additional loss due to added wire. Where it comes into play in an HVDC grid is reducing the rate at which current rises in a fault scenario, thus reducing the needed rating for DC breakers.

As an example, if a fault were to occur in a zone where this breaker provides protection, the Load Commutator switch opens and redirects current towards the banks of IGBTs and arresters in the main breaker. The banks of IGBTs can open in a pre-calculated manner to limit current to a set value or breaker it entirely. In parallel with this action, the UFD is now opening to prevent current from going through the bypass. [7] This breaker may additionally be assisted by another DC breaker that is rated to break the current this lower current.

![Figure 2. Typical Current Flow](image2)

![Figure 3. Initial Flow of Fault Current](image3)

![Figure 4. Redirection of Fault Current to Main Breaker](image4)
B. Thyristor Valves

Thyristor valves are created by cascading multiple modules in series with one another and when certain amounts of current deem it to be needed, in parallel with each other. Thyristors are typically aired with appropriately-sized heat sinks that may be air cooled or even water cooled depending on the need to do so.

Thyristors are indeed semiconductor devices and can even be controlled using multiple methods with the two most popular ones being a current pulse or a light pulse applied to the gate.

As seen above, thyristors do not conduct current (minus a small amount of leakage) until a pulse on the gate activates them. They are able to withstand large amounts of voltage and have no voltage drop across them when conducting current [8].

Different forms of switching are used to rectifier current and is incredibly useful in transmission applications. With no moving parts, thyristor valves are reliable and robust and are quickly replacing older mercury arc rectifiers.

IV. HVDC TRANSMISSION IMPACTS

A. Advantages of Using HVDC Transmission

There are many advantages to HVDC over HVAC transmission [9-11]. The most notable of these is seen in the use of HVDC underwater transmission which has addition losses in AC systems. These additional AC losses are caused by the dielectric effect and the current required to charge and discharge the capacitance of an AC transmission line. Undersea cables have higher capacitance which heightens this lose. Because of this effect, HVDC systems allow for the increase in the capacitance of an existing power grid at a relatively low cost with a low wire profile. The wiring and pylon profile is also lower than AC for the same capacitance because HVDC lines can carry more power per conductance than AC and DC lines carry a lower constant voltage than an AC lines peak voltage. Since a higher voltage requires more insulation and a higher spacing between conductors, HVDC lines have a further reduced cost for a higher power as well as requiring fewer conductors. HVDC has reduced corona loses caused by high voltage peaks and non-zero resistances found in a line’s wire. These peak voltages result in an ionization of the air as electric fields around a conductor exceed its designed value. Another advantage is in connecting remote and distant areas to a power grid. HVDC systems allow the use of long haul end to end bulk power transmission lines without the need for installing intermediate taps and require fewer conductors than HVAC. This makes transmission for this function and for connecting distance power plants to the distribution grid more cost effective. Additionally, HVDC allows for power transmission between unsynchronized AC distributions systems. There many difficulties in synchronizing AC systems running using different controls systems that are eliminated by doing this. The stabilization DC transmission can give to an AC power grid without increasing the maximum short circuit current using fast acting emergency controls systems on the DC lines is yet another advantage DC transmission has over AC. This power flow regulation can be used in power systems or parallel AC line for its damping effect on signal oscillation.

B. Negative Effect of HVDC Transmission

While there are cost saving benefits to using HVDC transmission, the overall cost is much higher for an HVDC system. HVDC does have the ability to connect to AC grids, this requires costly inverter stations. A short in the connected AC system causes HVDC power faults, making this method less reliable. HVDC transmission also requires very expensive filter and reactive power compensation units. These are needed because converter substations use generate both current and voltage harmonics which requires reactive power consumption not found in HVDC systems. The substation limit for modern multi-terminal HVDC transmission is six to eight and for a single terminal HVDC transmission cannot be designed more than five substations. These substations must have an extremely minimal capacitance which is even lower than the more substations that are added. This restriction makes the design of HVDC systems complex and difficult to implement. Another design difficulty comes in grounding the system. HVDC can have a very dangerous step voltage that requires...
constant fall safe grounding of the system. The design is further complicated by designing the control and regulation systems for HVDC since a constant communication link to all terminals to control the power flow. The location of these HVDC lines requires some consideration in the design because the effects of HVDC transmission line on other systems. For starters, this type of transmission has high frequency components that cause radio noise in nearby communication lines. The current flow also causes electro-corrosion of underground metal installations because HVDC transmission has a much higher frequency electromagnetic field than AC. There was a time that people thought this high frequency field might be a cancer causing agent, but currently this is not believe to be an issue.

V. CHALLENGES AND R&D OUTLOOK

HVDC is a very effective means of transmission for a lot of cases yet there are still many challenges holding the field back. A majority of these challenges in some part are related to the costs of the system. HVDC is a newer technology that is currently under active development to reach where it needs to be to become the most viable option for a super grid. The furthering in offshore wind farm technologies and other clean resources bring a need to transmit power efficiently over long distances. Here AC power systems exhibit limitation in these longer distance transmission that force HVDC to become the most efficient and cost effective option especially when using underwater or underground transmission cables. The major challenges that tend to offset the increased system efficiency are losses and costs in conversion from AC to DC and back, the switching and costs of a HVDC breaker, maintenance costs, system availability and uptime, and complexity of controlling and operating multi-terminal HVDC connections [12].

A major Challenge is the high cost of the components of the HVDC system such as the converter and inverter units, the cables, and control systems. This is due in part to the lower market demand for HVDC systems at this time and the lower availability of parts and manufacturers for these systems. Due to the principal of supply and demand the costs of components for these systems are driven higher than an AC system for various transmission configurations [13]. The initial cost of a high voltage AC to DC converter is large as new technologies that make the conversion more efficient are expensive; there is room for improvement in cost efficiency of these devices. They take up a lot of space; offshore converters will need to be on platforms built in the ocean for HVDC transmission from wind-farms and every advancement in size could help lower costs for these offshore converter rigs. The costs of power conversion needs to be weighed against the money and power saved in the transmission by HVDC as for some cases HVDC is not going to be overall more cost effective in shorter distance transmission [14].

Another large challenge is in the control of Multi-terminal HVDC systems. These systems are going to be the future of the HVDC technology as they can save energy and become the first layers of the energy efficient super-grid. The majority of HVDC systems in use today are point to point transmission systems, but there is a large push into research and implementation of the Multi-terminal HVDC for the future [15]. These systems are much more complex than those of their HVAC counterparts as there must be good communication between all the terminals, the power flow must be controlled by the converters on each terminal, for this newer VSC (voltage source converters) are becoming the best option for this as they can more easily control the power flow than any of the older models for conversions such as the Mercury-Arc Rectifier or the LCC (line commutated converters). Multi-terminal connections will increase the ability to tap into DC lines easily when adding new connections. These systems can be used to level power grids and share power between multiple grids that operate on different frequencies at once. As of 2012 there were two operating multi-terminal HVDC connections, the Hydro Québec – New England transmission between Radisson, Sandy Pond and Nicole, and the connection between the mainland of Italy, and the islands of Sardinia and Corsica [16]. Further research in Multi-terminal connections include a possible connection linking the east and west coast U.S. grids and Texas, as well as research on creating a European supergrid connecting the multiple grids in the European union.

Further R&D will make these HVDC systems more reliable and will increase uptime rivaling that of the current AC transmission networks. Research needs in the expansion and building of higher capacity systems are becoming more evident and will be needed to create a feasible HVDC grid. So far the biggest block of ABB’s system is a 320 kV connection with 1150 MW of power, there has been an identified need and a future push to provide systems that can handle upwards of 2 GW of power over the network [17].

Standardization for these new HVDC is a must as there currently no worldwide accepted operating and building guide line for the systems. Creating standards would bring more uniform parts to the market lowering costs and increasing availability of replacement parts and initial installs of the system [12]. A major area where there is need for standardization is operating voltage, which could be useful in connecting new terminals to operating grids all functioning at the same DC voltage; running on the same voltage is not necessary but will decrease losses due to the conversion from one DC voltage to another. The HVDC breaker is a new emerging technology created by ABB to handle the need for effective switching of the DC loads. This has in the past been a challenge as there is a low fault tolerance for these systems and it was very difficult to safely cut off the circuit. This differed from AC systems as it is more difficult without the zero crossings AC networks have. Advances in this field would be in improving the costs and safety of these breakers, making DC systems safer and more operable.

Further Development in the field of HVDC would be a large help in making it a valuable source for transmission. This transmission system is will be an efficient means for creating a better super-grid as the long distance transmission capabilities are invaluable in creating a better more efficient and reliable grid.
VI. REAL WORLD APPLICATIONS

The subject of High-Voltage Direct Current (HVDC) is an incredibly popular topic when discussing the future of smart grid technology and increasing the efficiency of delivering power, specifically across long distances and when connecting two separate power grids together in order to distribute power across them. When approaching HVDC, it is important to have a little understanding about the systems that exist today. Worldwide, there are about 193 HVDC systems that are either planned, under construction, or existing [18]. These 193 HVDC systems is just the beginning when talking about applications that exist today or applications that have been announced or are under construction. In Europe, these systems are an important backbone for electrical power distribution because they exist as a straightforward solution to distribute power between countries with varying systems. This leads to a much more stable power system by providing more sources of power systems connected and in the future could lead to an interconnected smart grid between many different power systems by connecting these HVDC systems with multiple inputs and outputs on either end. Another benefit that HVDC provides is the ability to access power generation opportunities off the shores of many countries.

An example of the offshore benefit application of HVDC that is ongoing today can be seen in Germany. In response to the Fukushima disaster, by the year 2022, Germany has planned to completely eliminate all of their sources of nuclear energy by shutting the reactors down and decommissioning the nuclear plants [19]. As late as 2012, nuclear power accounted for around 25% of the total power production in the country [19]. As part of their plan to accomplish the goal of decommissioning all of their nuclear reactors. They will be investing a lot of time, money, and research into alternative options for energy, such as solar and wind energy. Germany has plans the increase their production of offshore wind power from 200 MW to 25 GW by the year 2030 [20]. As part of their solution to achieve this increase in power generation, they have opted to use HVDC transmission in order to extend the effective range that they can construct offshore wind turbines. While this does not completely make up for the loss of nuclear power, it is a good step to make up some ground. Germany is not alone in their efforts to increase offshore wind generation, Great Britain is producing over 1600 MW of power using wind generation and Denmark is producing over 850 MW of wind power [20]. Some of the challenges facing implementing this new technology comes from the sheer size of the projects and the structures they have to build in order to implement them successfully. Siemens, the company that has been contracted to implement many of these wind power projects is constructing the HVDC converting platforms, among other components. These converting platforms are weighing in at around 15,000 tons and must be placed in waters that are up to 70 meters deep, which is about twice the depth that these systems sit at currently [20].

Another example of current real world applications is the HVDC system that is to be constructed in Seoul, South Korea by Alstom. According to the International Energy Agency’s 2012 report, South Korea has had an increase in energy demand around 25% over the last decade alone. As part of their solution to address the growing need for power, South Korea has contracted Alstom to construct a HVDC line into an energy corridor about 33km in size around Seoul [21]. This HVDC line is around 500 kV and has approximately a 1.5 GW power capacity [21]. This HVDC line will carry power from a power plant in the west of South Korea to a more populated part of South Korea in the east. This project is an example of the increasing relevance in HVDC. While HVDC is primarily used in long distance applications, in this situation it is being used as a solution to deliver power to populated areas with only a short distance. This is not the only HVDC project that Alstom announced in October of 2014. According to their website, they signed 800 million euros worth of contracts for HVDC lines to be constructed [21]. These projects are spread across the globe and included South Korea, India, and Canada. The project in Canada will stretch 1,100 km and around 350 kV; it is being designed to transmit hydropower from an 824 MW plant to Newfoundland [21]. In India, Alstom is constructing an 800 kV 3000MW Ultra-High Voltage Direct Current (UHVDC) line in order to meet energy demands in other parts of the country [21]. As far as companies go, Alstom has been working with HVDC for some time, a few notable projects that they have undertaken include the world’s longest HVDC transmission system, which is in Brazil and measures 2375 km; it also delivers 3150 MW at 600 kV [21].

While there are many more examples of ongoing projects and real world applications, those discussed in this section give a good snapshot of the solutions HVDC offers to the world in terms of increased demand for power as well as transmitting power from locations that have a lot of energy to spare to more remote locations. This will ultimately drive the cost for energy in these regions down and allow them to increase their own local economies by creating jobs and increasing cash flow in the regions. In the near future, HVDC connections and lines may evolve to more than point to point connections to integrate future smart grid technologies with will further allow the balancing of power and loads across regions.

VII. RECENT RELATED RESEARCH

The HVDC technology based on voltage source converter (VSC) and pulse width modulation (PWM) has been widely used over the world. VSC-HVDC is usually applied in grid interconnection, renewable energy integration, and urban power supply projects. Currently, most VSC-HVDC projects use two level or three level converters. However, VSC-HVDC based on these converters has some drawbacks, such as low voltage level, harmonics, and slow recovery from faults. Recently, a new converter topology for VSC-HVDC, called the Modular Multi-level Converter (MMC), has been proposed and already drawn much attention from both the academia and industry sides. The first industry application of MMC-HVDC is the Trans Bay Cable project that links two cities in California through an underwater HVDC cable. Compared with the conventional VSC, this new converter topology has many obvious advantages, such as reducing...
loss, easy capacity upgrade, good electromagnetic compatibility performance, and fast fault recovery.

A. The Topology of MMC-HVDC

The main topology of the MMC is shown in Fig. 8. It can be noted that each MMC has six arms as the same with two or three voltage level converters. The key feature of MMC is that each arm of MMC is constituted of a freely chosen number of identical Sub-Modules (SM) and a reactance L connected serially. Some possible structures of SM are shown in Fig. 9.

B. Technical Features of MMC-HVDC

Compared with conventional SVCs, the advantages of MMC are summarized in the following [22, 23].

- The output of MMC is smoother and has much better harmonic performance. This feature reduces the cost since no filters are needed. The impact of MMC on transformers is also less than two and three level converters, so the requirements on the AC transformers are also lower.
- The modular structure and the multiple voltage level reduce the changing rate of the voltage and current. Therefore, MMC can use a low switching frequency (150Hz, for instance) [22]. This feature significantly reduces the energy loss and increase efficiency during the switching of devices.
- MMC-HVDC can contain some back up sub-modules, so that the failed sub-modules can be replaced in time, improving the reliability of the HVDC system.
- MMC can meet higher voltage and capacity requirements through adding the series SM to each arm. This upgrade method is easy to implement.
- Some protection chokes can be inserted into the arms. They do not disturb operation or generate over-voltage for the semiconductors. The protection chokes limit the AC-current, whenever the DC-Bus is short circuited in fault conditions [23].
- Since SM is a two-terminal device and the DC-link voltage can be controlled through switching states, there is no need to install DC capacitors. This feature saves the cost and facilitates fast fault-recovery due to the absence of DC capacitors with energy stored.

C. Application of MMC-HVDC in Failure Management of Multi Terminal-HVDC

With the development of HVDC, a multi-terminal (MT) HVDC system is very likely to occur. For a large MT-HVDC network, there is no perfect solution to deal with short-circuit fault till now. As a more flexible converter, MMC provides a possibility to manage the fault in MT-HVDC.

When a short-circuit fault occurs in a MT-HVDC system, all the relevant AC side converter stations and the AC side grid are not feasible for transmission. The fault branch needs to be isolated, while the fault’s influence on the AC side should be minimized and other branches should be resumed transmission as soon as possible. To accomplish fast fault recovery, a new SM is designed in [22] as shown in Fig. 10.

In normal operation, the SM in Fig. 10 represents an equivalent of two half-bridge sub-modules. The total expense for the semiconductors and the resulting losses are only slightly increased, owing to the addition of T5, which is normally on. In order to cut off fault currents T5 is turned off, resulting in voltage clamping and energy absorption. During voltage clamping, both capacitors are in parallel, ensuring minimized overvoltage [23].

This topology is tested in a MT-HVDC system shown in Fig. 11. A line-to-line fault between terminals A and B in the
DC system is occurring at t=0. In order to take into account some delay for fault recognition and communication, the clamping action is triggered 0.5ms after the fault.

Figure 11. Clamp ‑ Double sub ‑ module

The AC ‑ and DC ‑ currents for Converter 1#, as well as the resulting fault current supplied by the converters are shown in Fig. 12 and Fig. 13, respectively. As expected, the DC currents rise steeply until clamping state is triggered. As soon as clamping action starts, all currents are decreasing to zero in approximately one millisecond.

Figure 12. AC ‑ and DC ‑ currents for Converter 1#, Figure 13. The resulting fault current

Assuming a sufficiently fast mechanical switching action at the switchyard, power transmission may restart immediately after the faulty branch is disconnected from the network. After successful clearing of the fault, closing of the disconnect switches without any surge currents can be accomplished [23].

D. Disadvantages of MMC

Despite many advantages, MMC still has some technical issues that need notice. Since MMC uses multi ‑ level voltages and many sub ‑ modules, its control is more complex compared to two ‑ level converters. Large amount of computation and high ‑ speed communication to link the central control unit and thyristors are needed. Another disadvantage is that the MMC has capacitors in its sub ‑ modules. Therefore, although MMC don’t need filter and save some space, it actually take more space than a two ‑ level converter with the same power rate.

VIII. CONCLUSIONS

With the integration of renewable energy and the increasing demand of urban power supply over long ‑ distance transmission, HVDC has good conditions and potentials for development. Moreover, as the technology of power electronics progresses, the HVDC will become more economic and competitive than AC transmission. It is reasonable to infer that HVDC will receive sustained attention and industry investments in the future.

REFERENCES
