International Journal For Technological Research In Engineering
Volume 1, Issue 7, March-2014 *ISSN (Online): 2347 - 4718*

BASIC CONCEPTS AND VARIOUS TECHNIQUES OF HVDC CONVERTER FOR ADVANCE TRANSMISSION SYSTEM

Patel Mihir[1], Patel Piyush[2], Patel Darshan[3] , Prajapati Bhavna[4] , Maheshwari Nikita[5]
Department of Electrical Engineering
[1,3,4,5] Merchant College of Engineering, Gujarat, India.
[2] Scope College of Engineering, Bhopal, India.

***Abstract*: The information on the web is growing dramatically, without a help system; the users may spend lots of time on the web finding the information they are interested in. Web mining is used to discover and extract useful information from the World Wide Web. The main goal of web mining technique is to find user's access object automatically from the large amount of web log data. Web mining has been explored to different techniques Web structure mining, Web content mining and Web usage mining that have been used for the variety of the application. Web usage mining techniques used to discover usage pattern from web data, in order to understand and better serve the needs of web based applications. In preprocessing, pages on a web sites are processed to create proper structure of a web site. In usage mining, we count the support of all the data in the web log file to find frequent itemsets based on URL related analysis and classify the web pages in to two category i.e either its index page or content page. In Site recommendation phase, the web site is examined to find better ways to give proper navigate system to the user. Web Personalization is the capability to customize customer communication based on knowledge preferences and behaviours at the time of interaction. Here we proposed a new approach, which generate personalization process more accurate and less time consuming.**

***Keywords:* Personalized recommendation, Web usage mining, Data preparation, Web log.**

I. INTRODUCTION

An HVDC converter converts electric power from high voltage alternating current (AC) to high-voltage direct current (HVDC), or vice-versa. HVDC is used as an alternative to AC for transmitting electrical energy over long distances or between AC power systems of different frequencies. HVDC converters capable of converting up to two gigawatts (GW) and with voltage ratings of up to 900 kilovolts (kV) have been built, and even higher ratings are technically feasible. A complete converter station may contain several such converters in series and/or parallel.

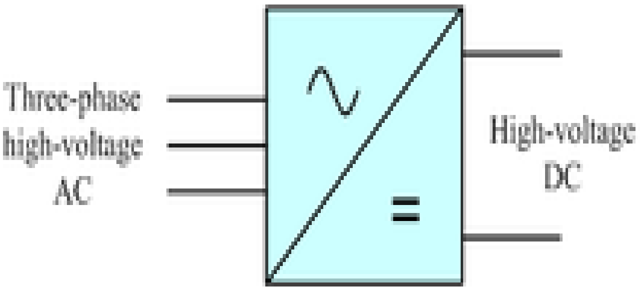


Fig.1. Symbol for HVDC converter

Almost all HVDC converters are inherently bi-directional; they can convert either from AC to DC (*rectification*) or from DC to AC (*inversion*). A complete HVDC system always includes at least one converter operating as a *rectifier* (converting AC to DC) and at least one operating as an *inverter* (converting DC to AC). Some HVDC systems take full advantage of this bi-directional property (for example, those designed for cross-border power trading, such as the Cross-Channel link between England and France).Others, for example those designed to export power from a remote power station such as the Itaipu scheme in Brazil, may be optimised for power flow in only one preferred direction. In such schemes, power flow in the non-preferred direction may have a reduced capacity or poorer efficiency. HVDC converters can take several different forms. Early HVDC systems, built until the 1930s, were effectively rotary converters and used electromechanical conversion with motor-generator sets connected in series on the DC side and in parallel on the AC side. However, all HVDC systems built since the 1940s have used electronic (static) converters.

Electronic converters for HVDC are divided into two main categories. *Line-commutated converters* are made with electronic switches that can only be turned on. *Voltage-sourced converters* are made with switching devices that can be turned both on and off. Line-commutated converters (LCC) used mercury-arc valves until the 1970s, or thyristors from the 1970s to the present day. Voltage-source converters (VSC), which first appeared in HVDC in 1997, use transistors, usually the Insulated-gate bipolar transistor (IGBT).

As of 2012, both the line-commutated and voltage-source technologies are important, with line-commutated converters used mainly where very high capacity and efficiency are needed, and voltage-source converters used mainly for interconnecting weak AC systems, for connecting large-scale wind power to the grid or for HVDC interconnections that are likely to be expanded to become *Multi-terminal* HVDC systems in future. The market for voltage-source converter HVDC is growing fast, driven partly by the surge in investment in offshore wind power, with one particular type of converter, the Modular Multi-Level Converter (MMC) emerging as a front-runner.

II. THE CONVERSION PROCESS

A. HVDC converter

At the heart of an HVDC converter station, the equipment which performs the conversion between AC and DC is referred to as the *converter*. Almost all HVDC converters are inherently capable of converting from AC to DC (*rectification*) or from DC to AC (*inversion*), although in many HVDC systems, the system as a whole is optimised for power flow in only one direction. Irrespective of how the converter itself is designed, the station which is operating (at a given time) with power flow from AC to DC is referred to as the *rectifier* and the station which is operating with power flow from DC to AC is referred to as the *inverter*.

Early HVDC systems used electromechanical conversion (the Thury system) but all HVDC systems built since the 1940s have used electronic (static) converters. Electronic converters for HVDC are divided into two main categories:

a. Line-commutated converters (LCC)
b. Voltage-sourced converters, or current-source converters.

a. Line-commutated converters

Most of the HVDC systems in operation today are based on line-commutated converters.

The basic LCC configuration uses a three-phase bridge rectifier or *six-pulse bridge*, containing six electronic switches, each connecting one of the three phases to one of the two DC rails. A complete switching element is usually referred to as a *valve*, irrespective of its construction. However, with a phase change only every 60°, considerable harmonic distortion is produced at both the DC and AC terminals when this arrangement is used.

An enhancement of this arrangement uses 12 valves in a *twelve-pulse bridge*. The AC is split into two separate three phase supplies before transformation. One of the sets of supplies is then configured to have a star (wye) secondary, the other a delta secondary, establishing a 30° phase difference between the two sets of three phases. With twelve valves connecting each of the two sets of three phases to the two DC rails, there is a phase change every 30°, and harmonics are considerably reduced. For this reason the twelve-pulse system has become standard on most line-commutated converter HVDC systems built since the 1970s.

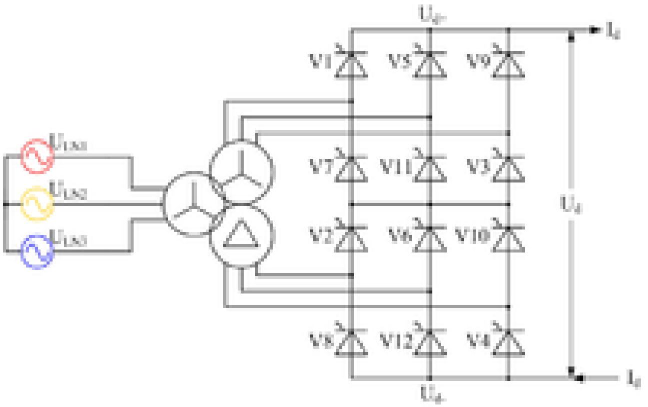


Fig.2. A twelve-pulse bridge rectifier

With line commutated converters, the converter has only one degree of freedom – the *firing angle*, which represents the time delay between the voltage across a valve becoming positive (at which point the valve would start to conduct if it were made from diodes) and the thyristors being turned on. The DC output voltage of the converter steadily becomes less positive as the firing angle is increased: firing angles of up to 90° correspond to rectification and result in positive DC voltages, while firing angles above 90° correspond to inversion and result in negative DC voltages. The practical upper limit for the firing angle is about 150–160° because above this, the valve would have insufficient *turn-off time*.

Early LCC systems used mercury-arc valves, which were rugged but required high maintenance. Because of this, many mercury-arc HVDC systems were built with bypass switchgear across each six-pulse bridge so that the HVDC scheme could be operated in six-pulse mode for short periods of maintenance. The last mercury arc system was shut down in 2012.

The thyristor valve was first used in HVDC systems in 1972. The thyristor is a solid-state semiconductor device similar to the diode, but with an extra control terminal that is used to switch the device on at a particular instant during the AC cycle. Because the voltages in HVDC systems, up to 800 kV in some cases, far exceed the breakdown voltages of the thyristors used, HVDC thyristor valves are built using large numbers of thyristors in series. Additional passive components such as grading capacitors and resistors need to be connected in parallel with each thyristor in order to ensure that the voltage across the valve is evenly shared between the thyristors. The thyristor plus its grading circuits and other auxiliary equipment is known as a *thyristor level*.

Fig.3. Thyristor valve stacks for Pole 2 of the HVDC Inter-Island between the North and South Islands of New Zealand. The man at the bottom gives scale to the size of the valves.

Each thyristor valve will typically contain tens or hundreds of thyristor levels, each operating at a different (high) potential with respect to earth. The command information to turn on the thyristors therefore cannot simply be sent using a wire connection – it needs to be isolated. The isolation method can be magnetic but is usually optical. Two optical methods are used: indirect and direct optical triggering. In the indirect optical triggering method, low-voltage control electronics send light pulses along optical fibres to the *high-side* control electronics, which derives its power from the voltage across each thyristor. The alternative direct optical triggering method dispenses with most of the high-side electronics, instead using light pulses from the control electronics to switch light-triggered thyristors (LTTs), although a small monitoring electronics unit may still be required for protection of the valve.

In a line-commutated converter, the DC current (usually) cannot change direction; it flows through a large inductance and can be considered almost constant. On the AC side, the converter behaves approximately as a current source, injecting both grid-frequency and harmonic currents into the AC network. For this reason, a line commutated converter for HVDC is also considered as a *current-source inverter*.

B. Voltage-sourced converters

Because thyristors can only be turned on (not off) by control action, the control system only has one degree of freedom – when to turn on the thyristor. This is an important limitation in some circumstances.

With some other types of semiconductor device such as the insulated-gate bipolar transistor (IGBT), both turn-on and turn-off can be controlled, giving a second degree of freedom. As a result, they can be used to make *self-commutated converters*. In such converters, the polarity of DC voltage is usually fixed and the DC voltage, being smoothed by a large capacitance, can be considered constant. For this reason, an HVDC converter using IGBTs is usually referred to as a *voltage sourced converter*. The additional controllability gives many advantages, notably the ability to switch the IGBTs on and off many times per cycle in order to improve the harmonic performance. Being self-commutated, the converter no longer relies on synchronous machines in the AC system for its operation. A voltage sourced converter can therefore feed power to an AC network consisting only of passive loads, something which is impossible with LCC HVDC.

HVDC systems based on voltage sourced converters normally use the six-pulse connection because the converter produces much less harmonic distortion than a comparable LCC and the twelve-pulse connection is unnecessary.

Most of the VSC HVDC systems built until 2012 were based on the *two level converter*, which can be thought of as a six pulse bridge in which the thyristors have been replaced by IGBTs with inverse-parallel diodes, and the DC smoothing reactors have been replaced by DC smoothing capacitors. Such converters derive their name from the discrete, two voltage levels at the AC output of each phase that correspond to the electrical potentials of the positive and negative DC terminals. Pulse-width modulation (PWM) is usually used to improve the harmonic distortion of the converter.

Some HVDC systems have been built with *three level converters*, but today most new VSC HVDC systems are being built with some form of *multi-level converter*, most commonly the *Modular Multi-Level Converter* (MMC), in which each valve consists of a number of independent converter submodules, each containing its own storage capacitor. The IGBTs in each submodule either bypass the capacitor or connect it into the circuit, allowing the valve to synthesize a stepped voltage with very low levels of harmonic distortion.

III. TYPES OF CONVERTERS

A. Current-Source Converters (CSCs)

The CSC-HVDC systems (also referred to as classic or conventional HVDC) represent mature technology today. This technology is well established for high power, typically around 1000 MW, and uses thyristor valves, as shown in Fig. 1 [5]. Such converters require a synchronous voltage source in order to operate. The basic building block used for HVDC conversion is the three-phase, full-wave bridge referred to as a 6-pulse, or Graetz, bridge. The term 6-pulse is due to six commutations or switching operations per period resulting in a characteristic harmonic ripple of 6 times the fundamental frequency in the DC output voltage. Each 6-pulse bridge is comprised of 6 controlled switching elements or thyristor valves. Each valve is comprised of a suitable number of seriesconnected thyristors to achieve the desired DC voltage rating.

The DC terminals of two 6-pulse bridges with AC voltage sources phase displaced by 30 degrees can be connected in series to increase the DC voltage and eliminate some of the characteristic AC current and DC voltage harmonics. Operation in this manner is referred to as 12-pulse operation.In 12-pulse operation the characteristic AC current and DC voltage harmonics have frequencies of 12n±1 and 12n respectively. The 30 degree phase displacement is achieved by feeding one bridge through a transformer with a wyeconnected secondary and the other bridge through a transformer with a delta-connected secondary.Most modern HVDC transmission schemes utilize 12-pulse converters to reduce the harmonic filtering requirements required for 6-pulse operation, e.g., 5th and 7thon the AC side and 6th on the DC side. This is because, although these harmonic currents still flow through the valves and the transformer windings, they are 180 degrees out of phase and cancel out on the primary side of the converter transformer.

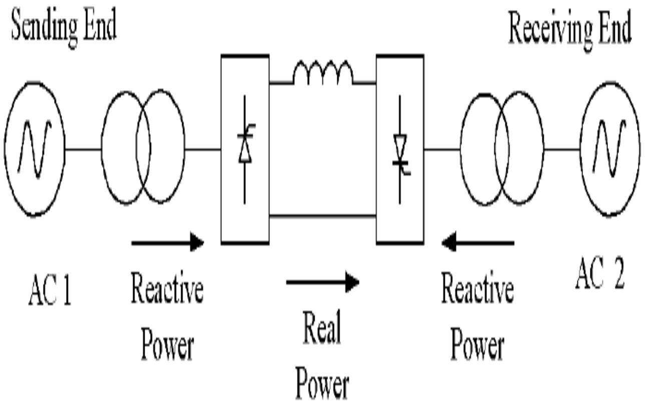


Fig.4. HVDC system based on CSC technology with thyristors.

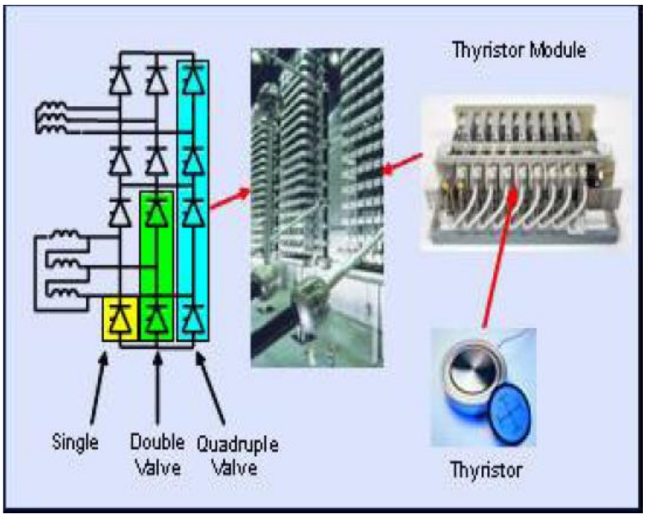


Fig.5. HVDC thyristor valve arrangement.

Fig. 2 shows the thyristor valve arrangement for a 12 pulse converter with three quadruple valves, one for each phase. Each thyristor valve is built up with series-connected thyristor modules. Each thyristor valve is built up with series-connected thyristor modules [6]. Line-commutated converters require a relatively strong synchronous voltage source in order to commutate. The three phase symmetrical short circuit capacity available from the network at the converter connection point should be at least twice the converter rating for converter operation. Linecommutated CSCs can only operate with the AC current lagging the voltage so the conversion process demands reactive power [6]. A summary of the CSC-HVDC system configurations is introduced in [5]. The largest and longest CSC-HVDC projects details are illustrated in [7]. Recently, there have been a number of significant advances, where the developments associated with the CSCs technology, are well documented in [8],[9]. The CSC-HVDC configurations are also applied with some modifications to the VSC-HVDC ones. Part I of this paper outlined different VSC-HVDC schemes, while the following part will explain the VSCs technology in details.

B. Voltage-source converters

Because thyristors can only be turned on (not off) by control action, and rely on the external AC system to effect the turn-off process, the control system only has one degree of freedom – when to turn on the thyristor.This limits the usefulness of HVDC in some circumstances because it means that the AC system to which the HVDC converter is connected must always contain synchronous machines in order to provide the commutating voltage – the HVDC converter cannot feed power into a passive system.

With some other types of semiconductor device such as the insulated-gate bipolar transistor (IGBT), both turn-on and turn-off can be controlled, giving a second degree of freedom. As a result, IGBTs can be used to make *self-commutated converters*. In such converters, the polarity of DC voltage is usually fixed and the DC voltage, being smoothed by a large capacitance, can be considered constant. For this reason, an HVDC converter using IGBTs is usually referred to as a *voltage-source converter*. The additional controllability gives many advantages, notably the ability to switch the IGBTs on and off many times per cycle in order to improve the harmonic performance, and the fact that (being self-commutated) the converter no longer relies on synchronous machines in the AC system for its operation. A voltage-sourced converter can therefore feed power to an AC network consisting only of passive loads, something which is impossible with LCC HVDC. Voltage-source converters are also considerably more compact than line-commutated converters (mainly because much less harmonic filtering is needed) and are preferable to line-commutated converters in locations where space is at a premium, for example on offshore platforms.

In contrast to line-commutated HVDC converters, voltage-source converters maintain a constant polarity of DC voltage and power reversal is achieved instead by reversing the direction of current. This makes voltage-source converters much easier to connect into a *Multi-terminal* HVDC system or “DC Grid”.

HVDC systems based on voltage-source converters normally use the six-pulse connection because the converter produces much less harmonic distortion than a comparable LCC and the twelve-pulse connection is unnecessary. This simplifies the construction of the converter transformer. However, there are several different configurations of voltage-source converter and research is continuing to take place into new alternatives.

C. Two-level converter

From the very first VSC-HVDC scheme installed (the Hellsjön experimental link commissioned in Sweden in 1997) until 2012, most of the VSC HVDC systems built were based on the *two level converter*. The two-level converter is the simplest type of three-phase voltage-source converter and can be thought of as a six pulse bridge in which the thyristors have been replaced by IGBTs with inverse-parallel diodes, and the DC smoothing reactors have been replaced by DC smoothing capacitors. Such converters derive their name from the fact that the voltage at the AC output of each phase is switched between two discrete voltage levels, corresponding to the electrical potentials of the positive and negative DC terminals. When the upper of the two valves in a phase is turned on, the AC output terminal is connected to the positive DC terminal, resulting in an output voltage of +½ U_d with respect to the midpoint potential of the converter. Conversely when the lower valve in a phase is turned on, the AC output terminal is connected to the negative DC terminal, resulting in an output voltage of -½ U_d. The two valves corresponding to one phase must never be turned on simultaneously, as this would result in an uncontrolled discharge of the DC capacitor, risking severe damage to the converter equipment.

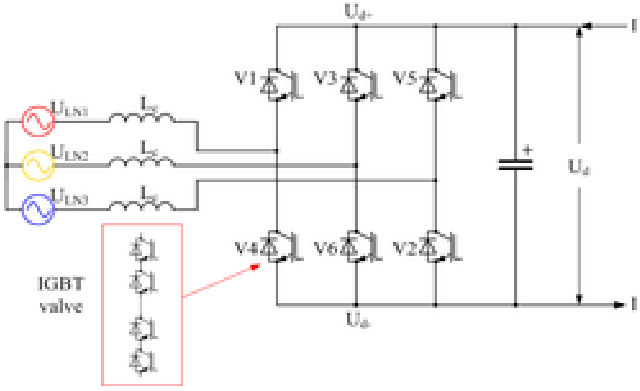


Fig.6. Three-phase, two-level voltage-source converter for HVDC

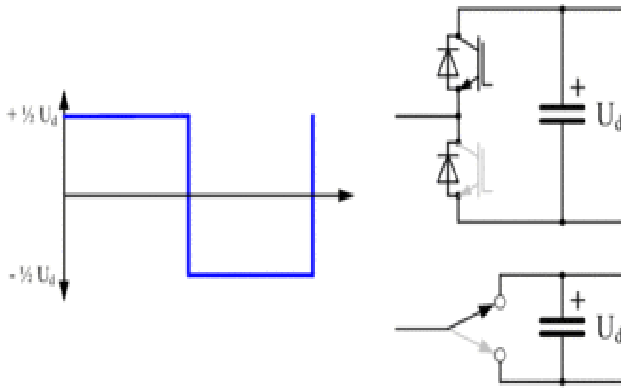


Fig.7. Operating principle of 2-level converter, single-phase representation

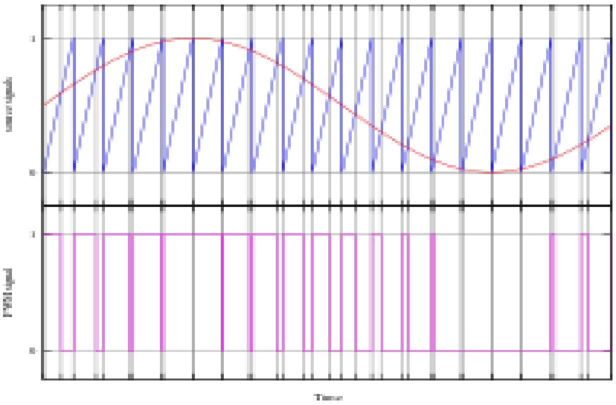


Fig.8. One method of generating the PWM pulse train corresponding to a given signal is the intersective PWM: the signal (here the red sinewave) is compared with a sawtooth waveform (blue). When the latter is less than the former, the PWM signal (magenta) is in high state (1). Otherwise it is in the low state (0).

The simplest (and also, the highest-amplitude) waveform that can be produced by a two-level converter is a square wave; however this would produce unacceptable levels of harmonic distortion, so some form of Pulse-width modulation (PWM) is always used to improve the harmonic distortion of the converter. As a result of the PWM, the IGBTs are switched on and off many times (typically 20) in each mains cycle.This results in high *switching losses* in the IGBTs and reduces the overall transmission efficiency. Several different PWM strategies are possible for HVDC but in all cases the efficiency of the two-level converter is significantly poorer than that of a LCC because of the higher switching losses. A typical LCC HVDC converter station has power losses of around 0.7% at full load (per end, excluding the HVDC line or cable) while with 2-level voltage-source converters the equivalent figure is 2-3% per end.

Another disadvantage of the two-level converter is that, in order to achieve the very high operating voltages required for an HVDC scheme, several hundred IGBTs have to be connected in series and switched simultaneously in each valve. This requires specialized types of IGBT with sophisticated *gate drive* circuits, and can lead to very high levels of electromagnetic interference.

D. Three-level converter

In an attempt to improve on the poor harmonic performance of the two-level converter, some HVDC systems have been built with *three level converters*. Three-level converters can synthesize three (instead of only two) discrete voltage levels at the AC terminal of each phase: +½ U_d, 0 and -½ U_d. A common type of three-level converter is the *diode-clamped* (or *neutral-point-clamped*) converter, where each phase contains four IGBT valves, each rated at half of the DC line to line voltage, along with two clamping diode valves.The DC capacitor is split into two series-connected branches, with the clamping diode valves connected between the capacitor midpoint and the one-quarter and three-quarter points on each phase. To obtain a positive output voltage (+½ U_d) the top two IGBT valves are turned on, to obtain a negative output voltage (-½ U_d) the bottom two IGBT valves are turned on and to obtain zero output voltage the middle two IGBT valves are turned on. In this latter state, the two clamping diode valves complete the current path through the phase.

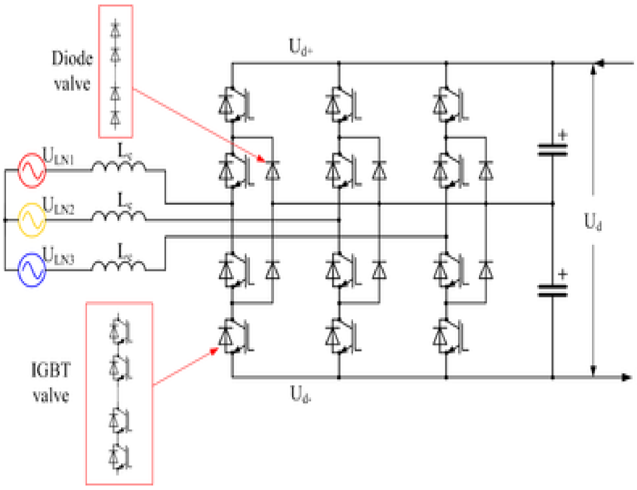


Fig.9. Three-phase, three-level, diode-clamped voltage-source converter for HVDC

In a refinement of the diode-clamped converter, the so-called *active neutral-point clamped* converter, the clamping diode valves are replaced by IGBT valves, giving additional controllability. Such converters were used on the Murraylink project in Australia and the Cross Sound Cable link in the United States· However, the modest improvement in harmonic performance came at a considerable price in terms of increased complexity, and the design proved to be difficult to scale up to DC voltages higher than the ±150 kV used on those two projects.

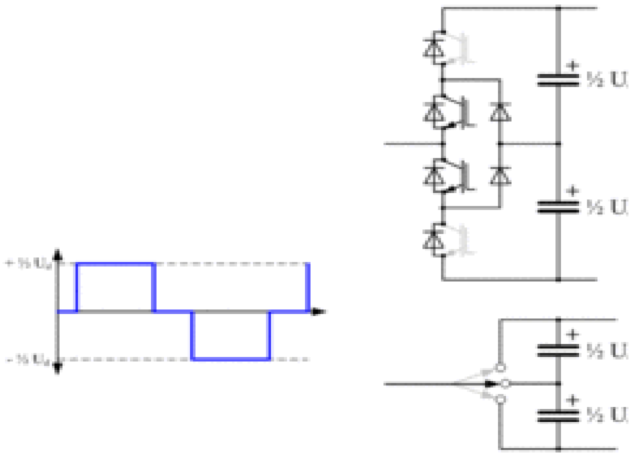


Fig.10. Operating principle of 3-level, diode-clamped converter, single-phase representation

Another type of three-level converter, used in some adjustable-speed drives but never in HVDC, replaces the clamping diode valves by a separate, isolated, *flying* capacitor connected between the one-quarter and three-quarter points.The operating principle is similar to that of the diode-clamped converter. Both the diode-clamped and flying capacitor variants of three-level converter can be extended to higher numbers of output levels (for example, five), but the complexity of the circuit increases disproportionately and such circuits have not been considered practical for HVDC applications.

E. Modular Multi-Level Converter (MMC)

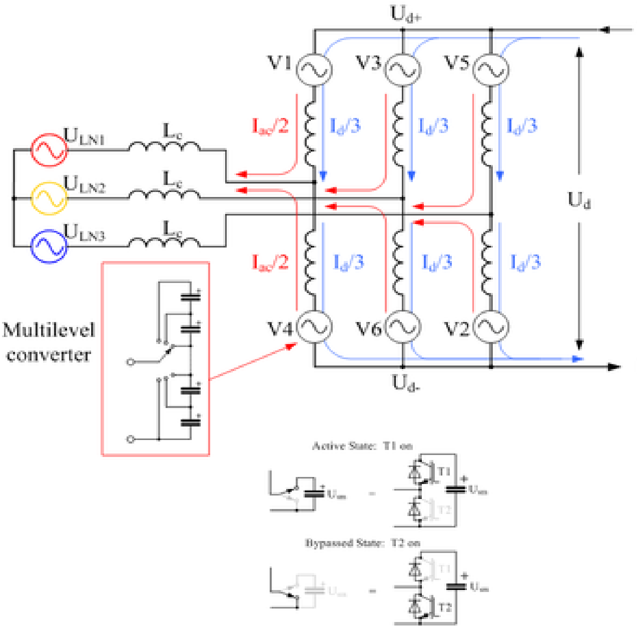


Fig.11. Three-phase Modular Multi-Level Converter (MMC) for HVDC.

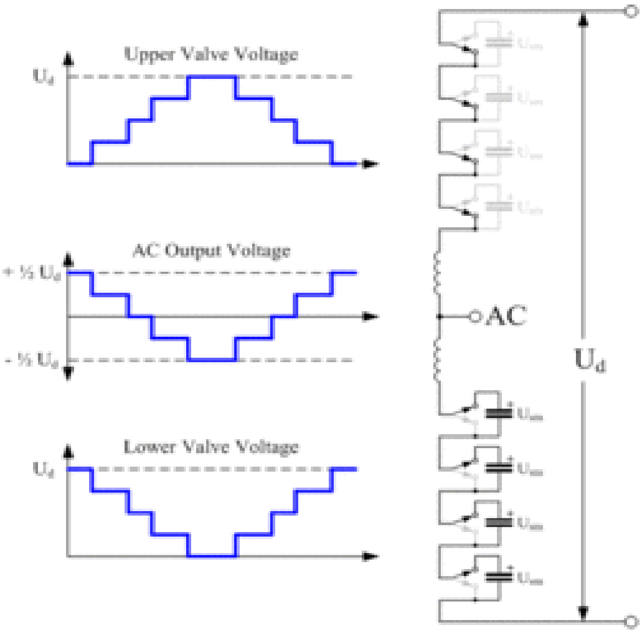


Fig.12. Operating principle of Modular Multi-Level Converter (MMC) for HVDC, with four series-connected submodules per valve. For clarity only one phase of the three is shown.

First proposed for HVDC applications in 2003 by Marquardt and first used commercially in the Trans Bay Cable project in Francisco, the *Modular Multi-Level Converter* (MMC) is now becoming the most common type of voltage-source converter for HVDC.

Like the two-level converter and the six-pulse line commutated converter, a MMC consists of six valves, each connecting one AC terminal to one DC terminal. However, where each valve of the two-level converter is effectively a high-voltage controlled switch consisting of a large number of IGBTs connected in series, each valve of a MMC is a separate controllable voltage source in its own right. Each MMC valve consists of a number of independent converter *submodules*, each containing its own storage capacitor. In the most common form of the circuit, the *half-bridge* variant, each submodule contains two IGBTs connected in series across the capacitor, with the midpoint connection and one of the two capacitor terminals brought out as external connections. Depending on which of the two IGBTs in each submodule is turned on, the capacitor is either bypassed or connected into the circuit. Each submodule therefore acts as an independent two-level converter generating a voltage of either 0 or U_{sm} (where U_{sm} is the submodule capacitor voltage). With a suitable number of submodules connected in series, the valve can synthesize a stepped voltage waveform that approximates very closely to a sine-wave and contains very low levels of harmonic distortion.

The MMC differs from other types of converter in that current flows continuously in all six valves of the converter throughout the mains-frequency cycle. As a result, concepts such as “on-state” and “off-state” have no meaning in the MMC.

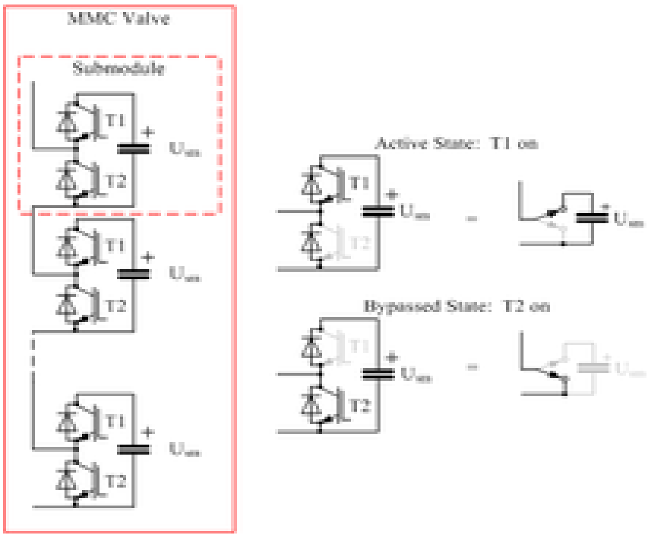


Fig.13. MMC valve showing possible conduction states

The direct current splits equally into the three phases and the alternating current splits equally into the upper and lower valve of each phase. The current in each valve is therefore related to the direct current I_d and alternating current I_{ac} as follows:

Upper valve: $$I_v = \frac{I_d}{3} + \frac{I_{ac}}{2}$$

Lower valve: $$I_v = \frac{I_d}{3} - \frac{I_{ac}}{2}$$

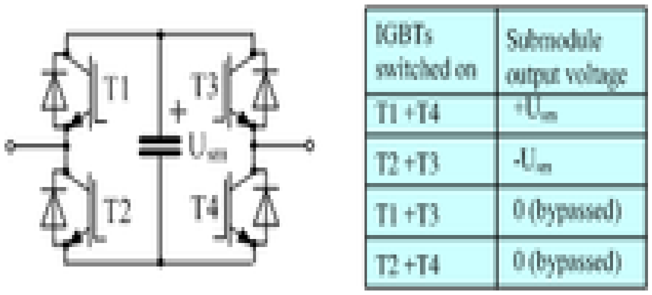
A typical MMC for an HVDC application contains around 300 submodules connected in series in each valve and is therefore equivalent to a 301 level converter. Consequently the harmonic performance is excellent and usually no filters are needed. A further advantage of the MMC is that PWM is not necessary, with the result that the power losses are much lower than those of the 2-level converter, at around 1% per end.Finally, because direct series-connection of IGBTs is not necessary, the IGBT gate drives do not need to be as sophisticated as those for a 2-level converter.

The MMC has two principal disadvantages. Firstly, the control is much more complex than that of a 2-level converter. Balancing the voltages of each of the submodule capacitors is a significant challenge and requires considerable computing power and high-speed communications between the central control unit and the valve. Secondly, the submodule capacitors themselves are large and bulky. A MMC is considerably larger than a comparable-rated 2-level converter, although this may be offset by the saving in space from not requiring filters.

As of 2012 the largest-capacity MMC HVDC system in operation is still the 400 MW Trans Bay Cable scheme but many larger schemes are under construction, including an underground cable interconnection from France to Spain consisting of two 1000 MW links in parallel at a voltage of ±320 kV.

F. MMC variants

A variant of the MMC, proposed by one manufacturer, involves connecting multiple IGBTs in series in each of the two switches that make up the submodule. This gives an output voltage waveform with fewer, larger, steps than the conventional MMC arrangement. This arrangement is referred to as the *Cascaded Two Level* (CTL) converter.Functionally it is exactly equivalent to the conventional half-bridge MMC in every respect except for the harmonic performance, which is slightly inferior – although still claimed to be good enough to avoid the need for filtering in most instances.



IGBTs switched on	Submodule output voltage
T1 +T4	$+U_{sm}$
T2 +T3	$-U_{sm}$
T1 +T3	0 (bypassed)
T2 +T4	0 (bypassed)

Fig.14. Full-bridge MMC submodule

Another alternative replaces the *half bridge* MMC submodule described above, with a *full bridge* submodule containing four IGBTs in an H bridge arrangement, instead of two·The full-bridge variant of MMC allows the submodule capacitor to be inserted into the circuit in either polarity. This confers additional flexibility in controlling the converter and allows the converter to block the fault current which arises from a short-circuit between the positive and negative DC terminals (something which is impossible with any of the preceding types of VSC). Furthermore it allows the DC voltage to be of either polarity (like a LCC HVDC scheme), giving rise to the possibility of hybrid LCC and VSC HVDC systems However, the full-bridge arrangement requires twice as many IGBTs and has higher power losses than the equivalent half-bridge arrangement.

IV. VOLTAGE-SOURCE VERSUS LINE-COMMUTATED CURRENT-SOURCE CONVERTERS

There is an inherent weakness with the conventional line commutated HVDC, i.e., the commutation of the converter valve is dependent on the stiffness of the alternating voltage supplied by the AC system. The converter cannot work properly if the connected AC system is weak and Substantial research has been performed in this field.The most outstanding contribution on this subject appeared which showed that the AC system can be considered as weak from two aspects: *i*) AC system impedance is high, and *ii*) AC system inertia is low. Either of the two network conditions may become an obstacle for HVDC applications.The newly developed PWM based VSCs have overcome the above weakness [35] and [40], and represent recent developments in the area of DC power transmission technology [10]. Different from the thyristor valves, where a relatively stiff alternating voltage of the AC system is a precondition for the valve commutation, the VSC can produce its own alternating-voltage waveform independent of the ACsystem. Thus, VSC-HVDC can even connect to a passive network with no other power source at all [41]-[42].Today, there are about 100 HVDC installations world-wide (in operation or planned for the very near future) transmitting high power and employing the two distinct technologies; the CSC and VSC-HVDC. The experience with VSC-HVDC at commercial level scatters over the last 14 years [12], [13]-[16],[17] and [43]-[45]. The breakthrough was made when the world’s first VSC-based PWM-controlled HVDC system using IGBTs was installed in March 1997 (Hellsjon project, Sweden,3 MW, 10 km distance, ±10 kV) [13], [14]. Since then, more VSC-HVDC systems have been installed worldwide.A beneficial summery table of the worldwide SC-HVDC projects and their basic parameters is introduced in [5]. The table contains the power rating, AC and DC voltage levels, DC cables lengths, converter topology (2 or 3-level), commissioning year, projects ‘names and targets, and the used semiconductors types. These worldwide projects cover different types of applications, e.g., back-to-back systems,wind energy applications, two controlled asynchronous connections for trading of electricity, power enhancement, and the powering of offshore platforms [15]-[17], and [19]-[22]. With the gradually reduced costs and losses, VSC-HVDC is becoming a competitive solution, which may extend the HVDC technology to broader applications than the traditional fields [43]-[45]. The recently proposed power-synchronization control for grid-connected VSCs has shown to be a feasible solution for VSC-HVDC connected to high-impedance weak AC systems, where the short-circuit capacity of the AC system is low [46]-[47]. By using power-synchronization control, the VSC emulates a synchronous machine. Therefore, it basically has no requirement on the short-circuit capacity of the AC system. On the other hand, the VSC contributes short-circuit capacity to the AC system, however, without increasing the short-circuit current during ac-system faults thanks to its current limitation capability.

V. HVDC INSTALLATIONS IN THE WORLD TODAY

Since the first commercial installation in 1954 a huge amount of HVDC transmission systems have been installed around the world. Figure 1 shows, by region, the different HVDC transmissions around the world.

A. Rationale for Choosing HVDC

There are many different reasons as to why HVDC was chosen in the above projects. A few of the reasons in selected projects are:

- In Itaipu, Brazil, HVDC was chosen to supply 50Hz power into a 60 Hz system; and to economically transmit large amount of hydro power (6300 MW) over large distances (800 km)
- In Leyte-Luzon Project in Philippines, HVDC was chosen to enable supply of bulk geothermal power across an island interconnection, and to improve stability to the Manila AC network
- In Rihand-Delhi Project in India, HVDC was chosen to transmit bulk (thermal) power (1500 MW) to Delhi, to ensure: minimum losses, least amount right-of-way, and better stability and control.
- In Garabi, an independent transmission project (ITP) transferring power from Argentina to Brazil, HVDC back-to-back system was chosen to ensure supply of 50 Hz bulk (1000MW) power to a 60 Hz system under a 20-year power supply contract.
- In Gotland, Sweden, HVDC was chosen to connect a newly developed wind power site to the main city of Visby, in consideration of the environmental sensitivity of the project area (an archaeological and tourist area) and improve power quality.
- In Queensland, Australia, HVDC was chosen in an ITP to interconnect two independent grids (of New South Wales and Queensland) to: enable electricity trading between the two systems (including change of direction of power flow); ensure very low environmental impact and reduce construction time.

VI. THE HVDC TECHNOLOGY

The fundamental process that occurs in an HVDC system is the conversion of electrical current from AC to DC (rectifier) at the transmitting end, and from DC to AC (inverter) at the receiving end. There are three ways of achieving conversion:

- Natural Commutated Converters. Natural commutated converters are most used in the HVDC systems as of today. The component that enables this conversion process is the thyristor, which is a controllable semiconductor that can carry very high currents (4000 A) and is able to block very high voltages (up to 10 kV). By means of connecting the thyristors in series it is possible to build up a thyristor valve, which is able to operate at very high voltages (several hundred of kV).The thyristor valve is operated at net frequency (50 hz or 60 hz) and by means of a control angle it is possible to change the DC voltage level of the bridge. This ability is the way by which the transmitted power is controlled rapidly and efficiently.
- Capacitor Commutated Converters (CCC). An improvement in the thyristor-based commutation, the CCC concept is characterised by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves. The commutation capacitors improve the commutation failure performance of the converters when connected to weak networks.
- Forced Commutated Converters. This type of converters introduces a spectrum of advantages,e.g. feed of passive networks (without generation), independent control of active and reactive power, power quality. The valves of these converters are built up with semiconductors with the ability not only to turn-on but also to turn-off. They are known as VSC (Voltage Source Converters). Two types of semiconductors are normally used in the voltage source converters:the GTO (Gate Turn-Off Thyristor) or the IGBT (Insulated Gate Bipolar Transistor). Both of them have been in frequent use in industrial applications since early eighties. The VSC commutates with high frequency (not with the net frequency). The operation of the converter is achieved by Pulse Width Modulation (PWM). With PWM it is possible to create any phase 3 angle and/or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Thus, PWM offers the possibility to control both active and reactive power independently. This makes the PWM Voltage Source Converter a close to ideal component in the transmission network. From a transmission network viewpoint, it acts as a motor or generator without mass that can control active and reactive power almost instantaneously.

VII. THE COMPONENTS OF AN HVDC TRANSMISSION SYSTEM

To assist the designers of transmission systems, the components that comprise the HVDC system, and the options available in these components, are presented and discussed. The three main elements of an HVDC system are: the converter station at the transmission and receiving ends, the transmission medium, and the electrodes.
The converter station: The converter stations at each end are replicas of each other and therefore consists of all the needed equipment for going from AC to DC or vice versa. The main component of a converter station are:

Thyristor valves: The thyristor valves can be build-up in different ways depending on the application and manufacturer. However, the most common way of arranging the thyristor valves is in a twelve-pulse group with three quadruple valves. Each single thyristor valve consists of a certain amount of series connected thyristors with their auxiliary circuits. All communication between the control equipment at earth potential and each thyristor at high potential, is done with fibre optics.

VSC valves: The VSC converter consists of two level or multilevel converter, phase-reactors and AC filters. Each single valve in the converter bridge is built up with a certain

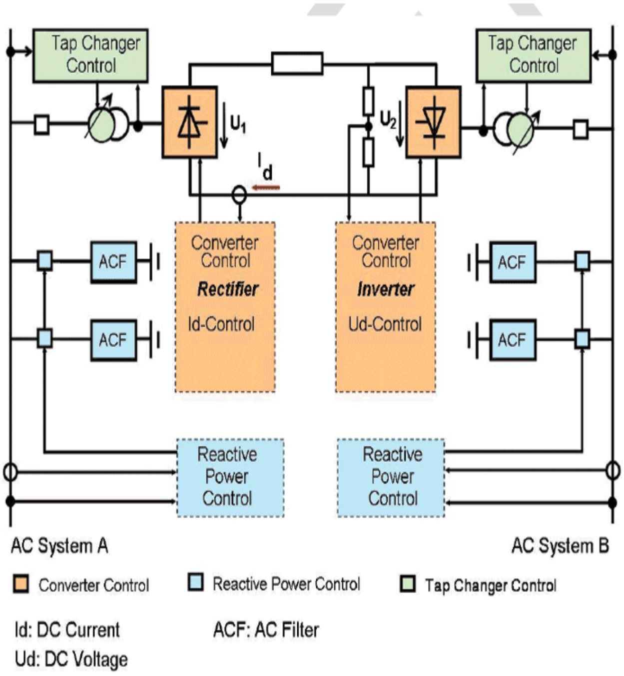


Fig.15. the components of an HVDC transmission system

number of seriesconnected IGBTs together with their auxiliary electronics. VSC valves, control equipment and cooling equipment would be in enclosures (such as standard shipping containers) which make transport and installation very easy.All modern HVDC valves are water-cooled and air insulated.

Transformers: The converter transformers adapt the AC voltage level to the DC voltage level and they contribute to the commutation reactance. Usually they are of the single phase three winding type, but depending on the transportation requirements and the rated power, they can be arranged in other ways.

AC Filters and Capacitor Banks: On the AC side of a 12-pulse HVDC converter, current harmonics of the order of 11, 13, 23, 25 and higher are generated. Filters are installed in order to limit the amount of harmonics to the level required by the network.. In the conversion process the converter consumes reactive power which is compensated in part by the filter banks and the rest by capacitor banks.In the case of the CCC the reactive power is compensated by the series capacitors installed in series between the converter valves and the converter transformer. The elimination of switched reactive power compensation equipment simplify the AC switchyard and minimise the number of circuit-breakers needed, which will reduce the area required for an HVDC station built with CCC. With VSC converters there is no need to compensate any reactive power consumed by the converter itself and the current harmonics on the AC side are related directly to the PWM frequency. Therefore the amount of filters in this type of converters is reduced dramatically compared with natural commutated converters.

DC filters: HVDC converters create harmonics in all operational modes. Such harmonics can create disturbances in telecommunication systems. Therefore, specially designed DC filters are used in order to reduce the disturbances. Usually no filters are needed for pure cable transmissions as well as for the Back-to-Back HVDC stations. However, it is necessary to install DC filters if an OH line is used in part or all the transmission system.The filters needed to take care of the harmonics generated on the DC end, are usually considerably smaller and less expensive than the filters on the AC side. The modern DC filters are the Active DC filters. In these filters the passive part is reduced to a minimum and modern power electronics is used to measure, invert and re-inject the harmonics, thus rendering the filtering very effective.

Transmission medium: For bulk power transmission over land, the most frequent transmission medium used is the overhead line.This overhead line is normally bipolar, i.e. two conductors with different polarity. HVDC cables are normally used for submarine transmission. The most common types of cables are the solid and the oil-filled ones. The solid type is in many cases the most economic one. Its insulation consists of paper tapes impregnated with a high viscosity oil. No length limitation exists for this type and designs are today available for depths of about 1000 m. The self –contained oil-filled cable is completely filled with a low viscosity oil and always works under pressure. The maximum length for this cable type seems to be around 60 km. The development of new power cable technologies has accelerated in recent years and today a new HVDC cable is available for HVDC underground or submarine power transmissions. This new HVDC cable is made of extruded polyethylene, and is used in VSC based HVDC systems.

VIII. CONTROL SYSTEM

The transfer of energy is controlled in the same way as for a classical HVDC connection: the rectifier side controls the dc voltage; the inverter side controls the active power. Like with classical HVDC the power flow can be in either direction. With classic HVDC the reactive power cannot be controlled independently of the active power. With VSC-HVDC there is an additional degree of freedom. VSC-HVDC using PWM technology makes it possible to control the reactive power and the active power independently. The reactive power flow can be controlled separately in each converter by the ac voltage that is requested or set manually without changing the dc voltage. The active power flow can be controlled by dc voltage on the dc side or the variation of frequency of ac side, or set manually. Thus, the active power flow, the reactive power flow, the ac voltage, the dc voltage and the frequency can be controlled when using VSC-HVDC. The control system of the VSC-HVDC is based on a fast inner current control loop controlling the ac current. The ac current references are supplied by the outer controllers. The outer controllers include the dc voltage controller, the ac voltage controller, the active power controller, the reactive power controller or the frequency controller. The reference value of the active current can be derived from the dc voltage controller, the active power controller and the frequency controller, the reference value of the reactive current can be obtained from the ac voltage controller, the reactive power controller. In all these controllers, integrators can be used to eliminate the steady state errors. For example, as shown in Figure 1, either side of the link can choose between ac voltage control and reactive power control. Each of these controllers generates a reference value for the inner current controller. The inner current controller calculates the voltage drop over the converter reactor that will lead to the desired current. Obviously not all controllers can be used at the same time. The choice of different kinds of controllers to calculate the reference values of the converter current will depend on the application and may require some advanced power system study. For example: the active power controller can be used to control the active power to/from the converter; the reactive power controller can be used to control the reactive power; the ac voltage controller which is usually used when the system supplies a passive network can be used to keep the ac voltage.

If the load is a passive system, then VSC-HVDC can control frequency and ac voltage. If the load is an established ac system, then the VSC-HVDC can control ac voltage and power flow. But it should be known that because the active power flow into the dc link must be balanced, the dc voltage controller is necessary to achieve power balance. Active power out from the network must equal the active power into the network minus the losses in the system; any difference would mean that the dc voltage in the system will rapidly change. The other converters can set any active power value within the limits for the system. The dc voltage controller will ensure active power balance in all cases.

IX. SIMULATION AND RESULTS

A. Simulink model

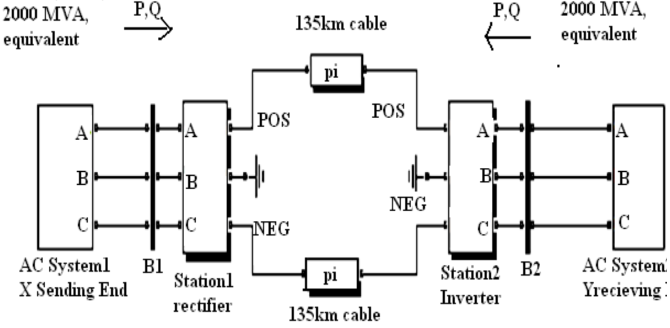


Fig.16. VSC-Based HVDC Transmission Link 315 MVA (+/-150kV)

B. System Description

A 300 MW (± 150 kV) forced-commutated voltage-sourced converter (VSC) interconnection is used to transmit DC power from a 400 kV, 2000 MVA, 50 Hz system to another identical AC system [17]. The AC systems (1 and 2) are modelled by damped L-R equivalents with an angle of 80 degrees at fundamental frequency and at the third harmonic. The rectifier and the inverter are three-level Neutral Point Clamped (NPC) VSC converters using close IGBT/Diodes. The rectifier and the inverter are interconnected through a 125 km cable (i.e. 2 pi sections) and two 8 mH smoothing reactors. The sinusoidal pulse width modulation (SPWM) switching uses a single-phase triangular carrier wave with a frequency of 27 time's fundamental frequency (1350 Hz). A converter transformer (Wye grounded /Delta) is used to permit the optimal voltage transformation. The present winding arrangement blocks tripplen harmonics produced by the converter. The 0.15 pu phase reactor with the 0.15 pu transformer leakage reactance permits the VSC output voltage to shift in phase and amplitude with respect to the AC system Point of Common Coupling (PCC) and allows control of converter active and reactive power output. The tap position is rather at a fixed position determined by a multiplication factor applied to the primary nominal voltage of the converter transformers. The multiplication factors are chosen to have a modulation index around 0.85 (transformer ratios of 0.915 on the rectifier side and 1.015 on the inverter side). To meet AC system harmonic specifications, AC filters form an essential part of the scheme. They can be connected as shunt elements on the AC system side or the converter side of the converter transformer. Since there are only high frequency harmonics, shunt filtering is therefore relatively small compared to the converter rating. The 78.5 Mvar shunt AC filters are 27th and 54th high-pass tuned around the two dominating harmonics.

C. Design Procedure

In the present work, the rectifier/inverter are three levels VSC that use the IGBT/diode module available in the MATLAB/Simulink/Simpower system. The case study is done for a VSC based HVDC transmission link rated 315 MVA (300MW, 0.95), ±150kv.

The system on AC side has: step down Y-Δ transformer, AC filters, Converter reactor. The system on DC side has: Capacitors and DC filters. The design of the components on AC and DC side are shown below. DC voltage rating: ±150kV System frequency: 50Hz Source AC voltage: 400kV line voltage Rated DC current=Rated DC power/Rated DC voltage

D. Ac System Modeling

AC system is modeled as a simple three phase AC source with internal resistance and inductance that is calculated from short circuit level MVA calculations. (MVA)B = 2000MVA

(KV) B = 400 kV (Phase to Phase rms) ; f=50Hz. Using these details, the Source inductance is found to be 0.2546H X=0.2546

E. Transformer Design

Y grounded /Δ Transformer is used to permit the optimal voltage transformation. It also blocks the triplen harmonics produced by the converter. The following data for the transformer is considered: Nominal Power =315MVA (total for three phases) Nominal frequency=50Hz. Winding1 specifications: Y connected, nominal voltage = 400kV rms (Line to Line) X 0.915 (to simulate a fixed tap ratio) = 366kV Resistance = 0.0025pu, Leakage reactance = 0.0075pu Winding 2 specifications: Δ connected, nominal voltage = 150kV rms (Line to Line), Resistance = 0.0025pu, Leakage reactance = 0.075pu Magnetizing losses at nominal voltage in % of nominal current: Resistive 5 %(=500pu), Inductive 5 % (500pu).

F. AC Filters

Three-phase harmonic filters are shunt elements that are used in power systems for decreasing voltage distortion and for power factor correction. Nonlinear elements such as power electronic converters generate harmonic currents or harmonic voltages, which are injected into power system. The resulting distorted currents flowing through system impedance produce harmonic voltage distortion. Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths. Harmonic filters are designed to be capacitive at fundamental frequency, so that they are also used for producing reactive power required by converters and for power factor correction. In order to achieve an acceptable distortion, several banks of filters of different types are usually connected in parallel. The most commonly used filter types are Band-pass filters, which are used to filter lowest order harmonics such as 5th, 7th, 11th, 13th, etc. Band-pass filters can be tuned at a single frequency (single-tuned filter) or at two frequencies (double-tuned filter).High-pass filters, which are used to filter high-order harmonics and cover a wide range of frequencies. A special type of high-pass filter, the C-type high-pass filter, is used to provide reactive power and avoid parallel resonances. It also allows filtering low order harmonics (such as 3rd), while keeping zero losses at fundamental frequency. The Three-Phase Harmonic Filter is built of RLC elements. The resistance, inductance, and capacitance values are determined from the filter type and from the following parameters: Reactive power at nominal voltage Tuning frequencies Quality factor. The quality factor is a measure of the sharpness of the tuning frequency. It is determined by the resistance value. The filter is made up of passive R, L,C components their values can be computed using specified nominal reactive power, tuning frequency and quality factor.

G. Transformer Design

Y grounded /Δ Transformer is used to permit the optimal voltage transformation. It also blocks the triplen harmonics produced by the converter. The following data for the transformer is considered: Nominal Power =315MVA (total for three phases) Nominal frequency=50Hz. Winding1 specifications: Y connected, nominal voltage = 400kV rms (Line to Line) X 0.915 (to simulate a fixed tap ratio) = 366kV Resistance = 0.0025pu, Leakage reactance = 0.0075pu Winding 2 specifications: Δ connected, nominal voltage = 150kV rms (Line to Line), Resistance = 0.0025pu, Leakage reactance = 0.075pu Magnetizing losses at nominal voltage in % of nominal current: Resistive 5 %(=500pu), Inductive 5 % (500pu).

H. AC Filters

Three-phase harmonic filters are shunt elements that are used in power systems for decreasing voltage distortion and for power factor correction. Nonlinear elements such as power electronic converters generate harmonic currents or harmonic voltages, which are injected into power system. The resulting distorted currents flowing through system impedance produce harmonic voltage distortion. Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths. Harmonic filters are designed to be capacitive at fundamental frequency, so that they are also used for producing reactive power required by converters and for power factor correction. In order to achieve an acceptable distortion, several banks of filters of different types are usually connected in parallel. The most commonly used filter types are Band-pass filters, which are used to filter lowest order harmonics such as 5th, 7th, 11th, 13th, etc. Band-pass filters can be tuned at a single frequency (single-tuned filter) or at two frequencies (double-tuned filter).High-pass filters, which are used to filter high-order harmonics and cover a wide range of frequencies. A special type of high-pass filter, the C-type high-pass filter, is used to provide reactive power and avoid parallel resonances. It also allows filtering low order harmonics (such as 3rd), while keeping zero losses at fundamental frequency. The Three-Phase Harmonic Filter is built of RLC elements. The resistance, inductance, and capacitance values are determined from the filter type and from the following parameters: Reactive power at nominal voltage Tuning frequencies Quality factor. The quality factor is a measure of the sharpness of the tuning frequency. It is determined by the resistance value. The filter is made up of passive R, L, C components their values can be computed using specified nominal reactive power, tuning frequency and quality factor.

Nominal voltage: 150kV Nominal frequency: 50Hz Nominal reactive power: 25% of real power (300MW) = 78.5Mvar Tuning frequency= 27*50 and 54*50. Quality factor= 15.

X. SIMULATIONS RESULTS

The simulation results at the sending end X and receiving end Y are illustrated in the following Figures.

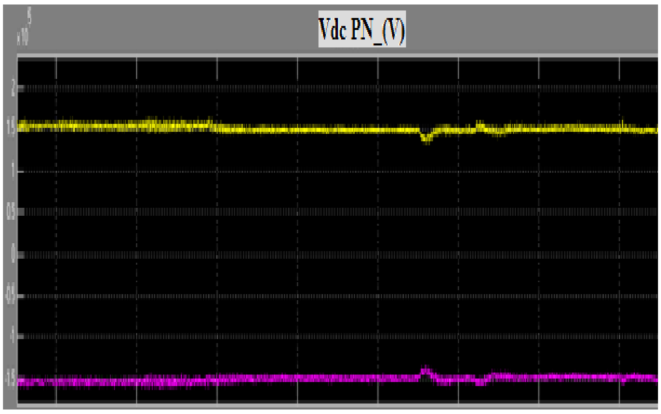


Fig.17. DC Voltage at receiving end

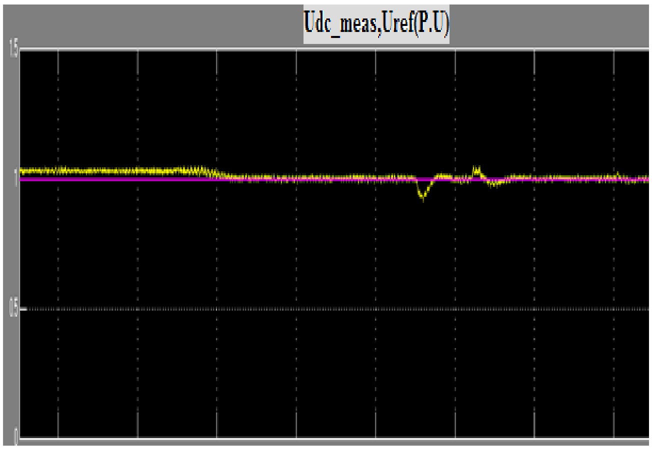


Fig.18. DC Voltage in p.u at receiving end

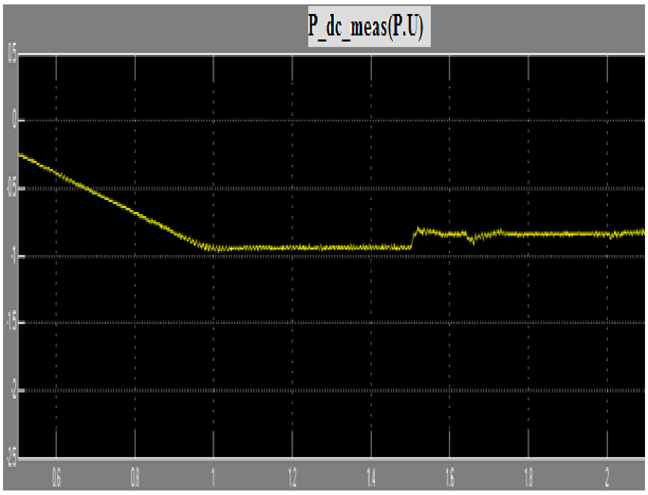


Fig.19. DC real power in p.u at receiving end (Y)

From the above simulation results it can be observed that by VSC HVDC transmission line, the reactive power at Y end can be minimized as well as the receiving end voltage can be maintained at 1pu without using any compensation.

XI. CONCLUSION

This Paper presents the steady-state performance of AC Transmission System and VSC based HVDC transmission system. The modelling details of HVDC system with three levels VSC are discussed. From the simulation results, it is concluded that the system response is fast; high quality ac voltages and ac currents can be obtained; and that the active power and the reactive power can be controlled independently and are bi-directional. The proposed scheme also ensures that, the receiving end voltage is maintained at 1 pu without any compensation.

REFERENCES

[1] M.Szechtman, T. Wess, C.V. Thio, "First *benchmark model forHVDC control studies*," ELECTRA, April 1991, pp. 55-73.

[2] M.Szechtman, T. Margaard, J.P. Wowles, C.V. Thio,D.Woodford, T. Wess, R. Joetten, G. Liss, M, Rashwan, P.C. Krishnayya, P.Pavlinec, V. Kovalev, K. Maier,J. gleadow, J.L: Haddock, N.Kaul, R.Bunch, R.Johnson, G.Dellepiane, N. Vovos. "The *CIGRE BenchMark Model – A New Proposal with Revised Parameters*," ELECTRA, December 1994, pp. 61-66.

[3] HVDC and FACTS Controllers, Vijay. K. Sood, USA, Kluwer Academic Publishers, 2004.

[4] Computer Modelling of Electrical Power Systems, Second Edition, J. Arrillaga, N.R. Watson, Institution of Electrical Engineers, John Wiley & Sons, England, 2001.

[5] Flexible ac transmission systems (FACTS), Jong Hua Song, Allan T. Johns, Institution of Electrical Engineers, London, U.K, 1999.

[6] High Voltage Direct Current Transmission, 2nd Edition, Jos. Arrillaga, Institution of Electrical Engineers, London, U.K, 1998.

[7] Direct Current Transmission, Volume I, Edward Wilson Kimbark, Wiley-Interscience, John Wiley & Sons, Canada, 1971.

[8] Power System Stability and Control. New York, Prabha Kundur, McGraw-Hill, Inc., 1993.

[9] Power Transmission by Direct Current, Erich Uhlmann, Springer-Verlag Berlin Heidelberg New York, 1975.

[10] HVDC Power System Transmission Systems, K. R. Padiyar, New Age International (P) Limited, Publishers, 1990.

[11] Understanding FACTS, Narain G. Hingorani, Laszlo Gyugyi, IEEE Press, 2000.

[12] Electric Power Transmission System Engineering: Analysis and Design, Turan Gönen, Wiley-Interscience, John Wiley & Sons, USA, 1988.

[13] High Voltage Direct Current Power Transmission, Colin Adamson, N.G. Hingorani, Garraway Limited, London, England, 1960.

[14] Dynamic Modelling of Line and Capacitor Commutated Converters for HVDC Power Transmission, Dissertation

Thesis, Wolfgang Hammer, Swiss Fedral Institute of Technology Zurich,Switzerland, 2003.
[15] Analysis of Subsynchronous Resonance in Power Systems, K. R. Padiyar, USA, Kluwer Academic Publishers, 1999.
[16] Multi-Level Inverters for utility-Applications, Olaf Pollakowski, VDI Verlag GmbH, Düsseldorf, Germany, 1999.