Power Transmission by High Voltage Direct Current (HVDC)

B. R. Andersen
(ALSTOM T&D Power Electronic Systems Ltd.)

Abstract

지난 세기의 시작 이래로, 50Hz 또는 60Hz로 운영되는 교류는 전력 계통 망의 송전과 배전에 지배적으로 사용되는 방법이었다. 그러나, 일반적으로 HVDC라 불리는, 고압 직류 송전은 매우 긴 장거리 선로에 대한 경제적 해법을 제공하고 이미 실현된 비 동기화 AC계통 사이의 연계를 가능케 하였다. 50MW에서 6300MW까지의 각 Scheme별로 건설된 직류송전은 전세계적으로 총 59GW HVDC Scheme이 설치되어있으며, 이 기술을 위해서는 더 많은 응용이 고려되고 있다. 본 원고에서는 HVDC의 특성, 포함된 설비, HVDC의 사용 그리고 기술 발전의 요약을 기술하였다.

1. What is HVDC ?

In an ac network the power flowing in each transmission line is determined by the impedance of the line, as well as the voltage magnitude and phase angle at the two ends. The system operator can influence these by controlling generation, system transformer tapchangers and shunt or series reactive power elements.

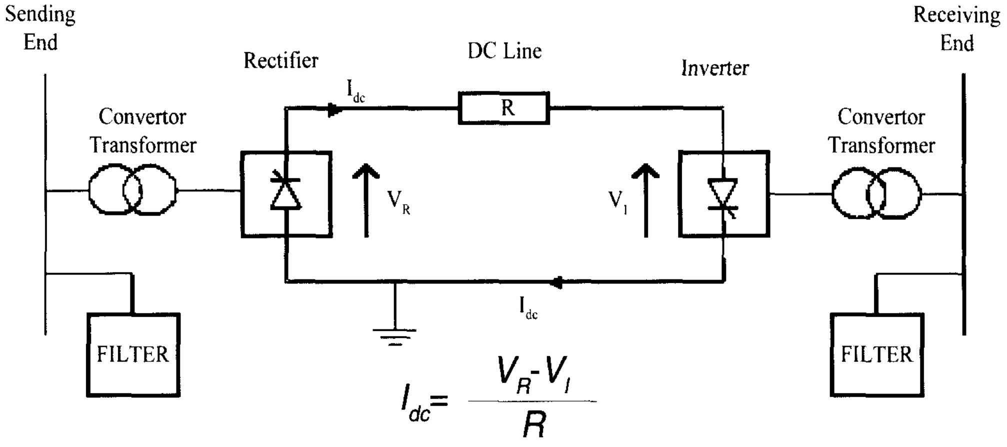


Figure 1 Basic HVDC Transmission

In an HVDC system, power electronics (a convertor) is used to convert ac power to dc power at one terminal (rectifier) and vice versa at the other terminal (inverter). A simple representation of a HVDC interconnection is shown in Figure 1. AC power is fed to a convertor operating as a rectifier. The output of this rectifier is dc power which is independent of the ac supply frequency and phase. The dc power is transmitted through some conduction medium be it an overhead line, a cable or a short length of busbar and applied to the dc terminals of a second convertor. This second convertor is operated as a line commutated inverter and allows the power to flow into the receiving ac network.

The convertor transformers in Figure 1 provide galvanic isolation and suitable adjustment of the voltage magnitude, by means of their tap-changers.

Conventional HVDC transmission is therefore termed line commutated thyristor technology. Consider a simplified representation of a thyristor as shown in Figure2. When a gate pulse (I_g) is applied while positive forward voltage is imposed between the anode and cathode (V_{THY}), the thyristor will conduct current (I_L). Conduction continues without further gate pulses as long as current flows in the forward direction. Thyristor "turn-off" takes place only when the current tries to reverse. Therefore a convertor comprising of thyristors requires an existing alternating ac voltage (V_{ac}) in order to operate as an inverter.

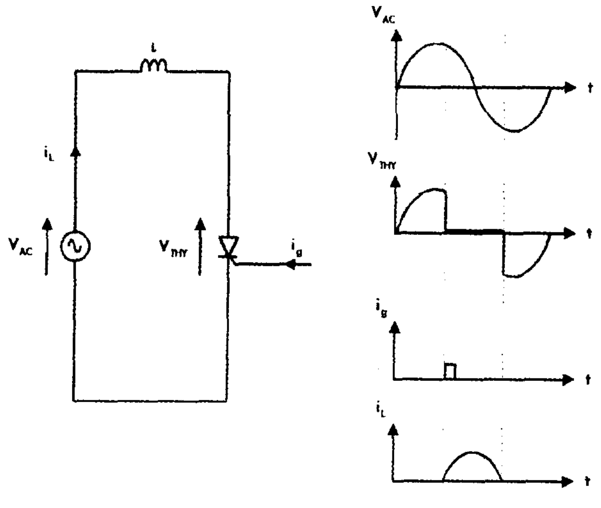
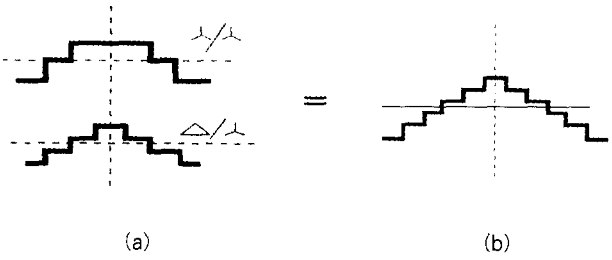


Figure 2 The Gating and Commutation of a Thyristor



(a) (b)

Figure 3 (a) The idealised AC current waveforms produced by two 6-pulse thyristor bridges, one connected to a star/star trasnsformer winding and the other connected to a delta/star transformer winding

(b) The resultant idealised AC current waveform when the two 6-pulse AC waveforms are added together at a common connection point (i.e. the convertor station AC busbar)

The basic building block of an HVDC convertor is the Graetz (or 6-pulse) bridge. The switching action of the bridge gives rise to harmonic voltages on the dc side and harmonic currents on the ac side. As shown in Figure 3, by connecting two Graetz bridges in series and energising one from a star-connected transformer winding and the other from a delta-connected transformer winding, the harmonics of the resultant waveform are reduced. The harmonics produced by the convertors may still need to be suppressed in order to avoid interference with other electrical equipment, particularly on the ac side. This is achieved by means of harmonic filters, which are shunt connected capacitor banks, with auxiliary R, L and C components to achieve the appropriate harmonic impedance characteristics.

The conversion of power from ac to dc and vice versa is done through the commutation process by the valves. In a line-commutated convertor the ac current will always lag the ac voltage, such that reactive power is absorbed both at the rectifier and the inverter. Typically, the reactive power is 50% of the real power. The ac harmonic filters are capacitive at fundamental frequency and provide compensation for the reactive power which is absorbed by the convertors. The filters are switched as the load varies to achieve satisfactory overall power factor. Normally, the filters are subdivided such that the ac voltage change on filter switching is acceptable.

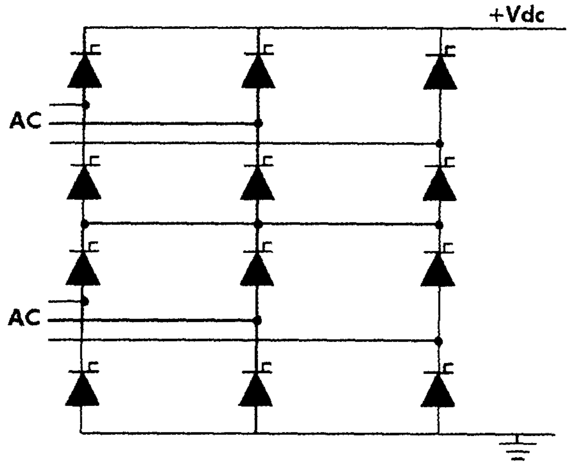


Figure 4 A 12-Pulse Convertor Bridge

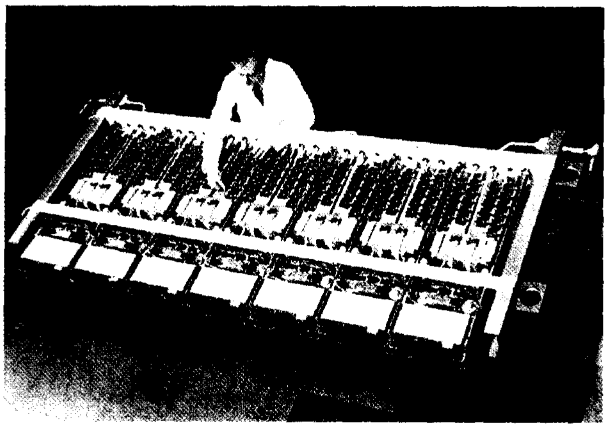


Figure 5 A Single "Semi-Tier" containing 14 series connected thyristors

Figure 4 shows two 6-pulse bridges combined to form a single 12-pulse convertor bridge. All modern HVDC schemes use this 12-pulse bridge arrangement. The practical implementation is as three "quadri-valves", the four valves in a phase being physically mounted on top of each other. Each "valve" within the bridge consists of many devices connected in series in order to obtain the necessary dc voltage for economic power transmission. Figure 5 shows an ALSTOM "Tier Assembly" consisting of 14 series connected 100mm diameter thyristors giving it a maximum power rating of over 100MW. Considering that the highest voltage rated scheme in service to date operates at 600kV dc and that the maximum peak voltage withstand capability of thyristors used in HVDC transmission is about 8.5kV, it is clear that many thyristors need to be connected in series to withstand the applied voltage.

The convertors are controlled by a multi-layered control system. At the lowest level very fast phase-locked oscillator control enables the dc current to be controlled within each power frequency cycle. Intermediate level control enables the power output to be varied automatically to benefit the ac network (eg power swing damping controls, reactive power and voltage controls, frequency control and emergency power control routines) At the highest levels the operator is provided with the tools required to change the power and other settings, monitor the performance and safely execute start/stop and other operating sequences.

2. What Use is HVDC?

To date HVDC power transmission has provided economic benefit in a number of areas the main ones being:

2.1 Bulk Power Transmission on Overhead Lines

HVDC links use power electronic equipment to convert ac to dc (and vice versa) at each terminal. This requires higher capital outlay than would be required for a substation for an ac interconnection. However, HVDC towers are simpler than ac towers because only two conductors are required for a monopolar HVDC link, which is equivalent to a single ac circuit. In some locations electrodes can be inserted into the earth (or sea), to provide the low voltage return path and in these circumstances only one metallic conductor is necessary. Also the wayleave occupied for dc transmission towers is less than that required for the equivalent ac power transmission. The ability, directly and instantaneously, to control the power transferred over an HVDC link can be used to benefit the ac system, providing further direct and indirect cost benefits in dc's favour.

Therefore, even though the cost of an HVDC terminal station is greater than that of an equivalent ac transmission substation, a "break even" distance can be defined beyond which it is more economic to transmit bulk power as dc instead of ac. This break-even distance varies depending on the economic factors influencing each case but is typically in the range of 800-1000km.

2.2 Power Transmission via Cable

The construction of a cable (conductor surrounded by insulation enclosed by an earth plane) means that it has a much higher capacitance than does an overhead line. When alternating voltage is imposed on a cable, not only does the load current flow through the core conductor but also a capacitive charging current. This charging current changes direction every half cycle, charging, discharging then re-charging the cable. Even for a cable of only moderate length (50km), this reactive charging current can utilise a major part of the total current carrying capability of the cable, severely limiting the amount of useful real power that can be transmitted. In the limit the ac capacitive charging current drawn by the cable approaches its total current carrying capacity, rendering the cable useless as a power transmission medium. Electrodes can also be used for cable schemes as the low voltage return path.

In the case of HVDC transmission, apart from an initial charging current, the cable draws no capacitive charging current. Therefore power can be transmitted through any length of cable, being limited only by the cost of the cable and economics of the I^2R losses incurred.

2.3 Transmission between Unsynchronised AC Systems

When two adjacent ac systems operate at different frequencies such as 50Hz and 60Hz, the only practical way to obtain the advantages of an interconnection between them is by means of a dc connection.

DC power is independent of the frequency and relative phase of the power systems. Therefore, power can be transmitted between two independent ac systems without applying any operational restrictions to either system. An asynchronous HVDC interconnection will not suffer from power swings and risk of tripping arising from overload, which may afflict an ac connection between two ac systems in the event of a fault in one of them. Therefore, even when ac networks operate at the same nominal frequency an interconnection by HVDC may be preferable to an ac interconnection. There are many examples of this in North America and in India often using Back-to-Back HVDC schemes, in which both terminals of the scheme are located at the same site.

2.4 Parallel AC and DC Transmission

When upgrading an ac system with additional transmission lines it may be advantageous to make some of them dc. The controllability of HVDC means that the power delivered can be modulated to give improved damping to the ac transmission, sometimes allowing additional power to be transmitted safely through the ac interconnection. One example of this application of HVDC is the West Coast Pacific Intertie in the United States of America, where a dc line was installed enabling the maximum voltage vectors between the ends of the parallel AC line to be increased thereby increasing the power transmission capacity of the line by about 20%(1) (as the maximum power transferable is proportional to the sine of the displacement angle).

2.5 Minimising Short Circuit Capacity Increases

As power demand increases additional ac infeeds are usually added. However, there may come a point where any further infeeds will increase the Short Circuit Level (SCL) in some part of the system beyond the rated capability of the existing ac switchgear. In order to avoid having to upgrade the existing ac switchgear whilst still delivering more power, HVDC could be used to import the additional power. During a fault in the ac system the infeed from the HVDC convertor is limited to a value no larger than the rated current very swiftly, so that the HVDC infeed does not contribute significantly to the fault current.

2.6 Upgrading Existing AC Transmission lines to DC

In many countries, along with increasing demand for more power, there is increasing environmental objections against constructing new overhead lines. One potential solution to this is to modify one, or more, existing ac lines to be used for HVDC power transmission. The dc power that can be transmitted down a given wayleave without affecting the visual impact is significantly greater than that which can be achieved with ac transmission and, as discussed above, the addition of a parallel dc connection can often increase the maximum safe power transfer through existing parallel ac lines.

3. The Development of New Power Semi-Conductor Devices

The main emphasis of power semi-conductor development over recent years has been towards more sophisticated "bimodal" devices such as the GTO (Gate Turn Off) thyristor and the IGBT (Insulated Gate Bipolar Transistor), which provide "turn-off" as well as "turn-on" capability, and do not have to rely on current zero and a voltage reversal being applied by the external circuit. Convertors using bimodal semi-conductor devices do not require an externally applied ac voltage for successful commutation, so they can be operated at any desired power factor. One application of these devices is in the Voltage Sourced Convertor (VSC) which has a relatively large capacitance on the dc side. The semi-conductors in a VSC scheme are used to connect the three ac phases to the dc capacitor at appropriate times. With bimodal devices comes the ability to use Pulse Width Modulation (PWM), which can be used to reduce the magnitude of the lower order harmonics produced by the convertor, compared with those produced by a conventional 12-pulse thyristor convertor.

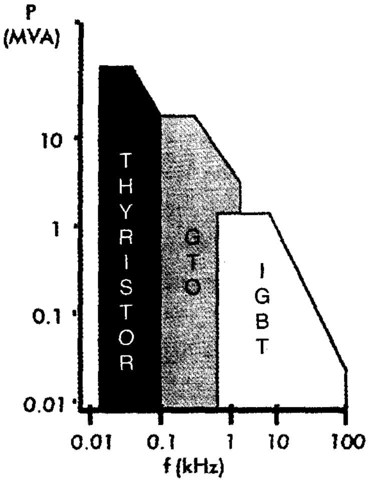


Figure 6 Comparative ratings of semi-conductor devices as a function of switching frequency

Much effort has also been invested in the development of Silicon Carbide (SiC) for semi-conductor devices. Compared with silicon, SiC has the advantage of a higher voltage withstand capability with a thinner wafer, which results in lower losses, and the ability to operate at higher temperature. The first SiC devices have been diodes which, when used in conjunction with some of the new bimodal devices, can enhance the overall performance of the convertor. The future development of SiC thyristors will enable significant cost and power loss reductions to be realised in thyristor based HVDC schemes.

Figure 6 shows a comparison between the power carrying capabilities of various semi-conductor devices based on presently available ratings, and indicates that increasing sophistication is achieved at the expense of rating. Of the bimodal devices, two types have been particularly taken up by industry, these being the GTO and the IGBT. Both of these power semi-conductor types have advantages and disadvantage depending upon the proposed application, but for industrial usage the IGBT presently is winning the largest market share and by far the biggest application of the IGBT has been in ac motor drives. The use of bimodal semiconductors allows PWM to be used with the following advantages for motor drives:

- A better approximation of a sine wave than is achievable with the thyristor bridge and hence lower losses in the motor.
- Excellent dynamic response
- Smooth torque/speed control
- Rides through dips in supply voltage
- Good ac power factor over full speed range

4. VSC Transmission System

Voltage Sourced Convertors can also be used for dc transmission and this application is known as VSC Transmission. An outline circuit diagram of a VSC

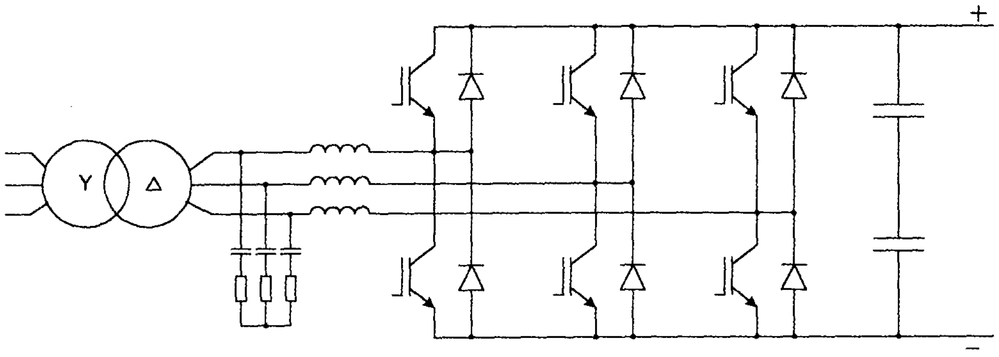
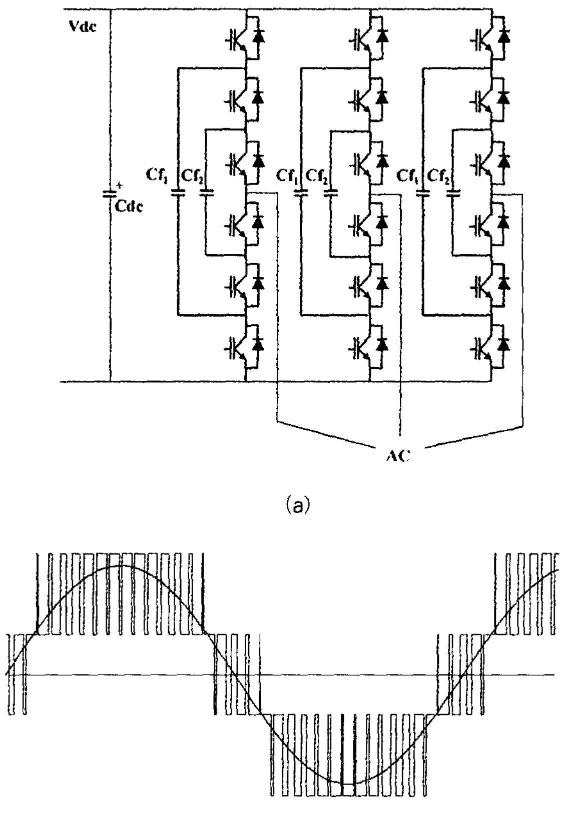


Figure 7 One terminal of a 2-level VSC Transmission scheme

Transmission System would look very similar to that shown in Figure 1. In its simplest form one terminal of a two-level convertor is used as shown in Figure 7. This six-pulse bridge uses IGBTs and anti-parallel connected freewheeling diodes.

The convertor can be likened to a very large motor drive. The ac voltage at its terminals is created by the controlled switching of the dc output to the ac terminals by means of the IGBTs. The phase angle and amplitude of the resulting waveform can be fully controlled. By using PWM switching it is possible to reduce the amplitude of low order harmonics. However, the more frequently the IGBTs are switched the higher the power losses. Thus a compromise needs to be made between waveform quality and power losses.

In a VSC Transmission system a single unswitched ac harmonic filter for high frequency harmonics is normally adequate. Thus the ac switchyard is much simpler than for a conventional HVDC scheme. The convertor transformers are normally simpler than a conventional HVDC convertor transformer and will not normally see a dc stress or high harmonics. A high frequency blocking filter is normally used between the transformer and the convertor.



(a)

(b)

Figure 8 (a): A four level capacitor clamped VSC
(b): Output Voltage wavefom of the convertor

An alternative configuration of VSC is shown in Figure 8(a). Here the VSC's semiconductor switches are configured in pairs of 'commutation cells', with 'floating capacitors' (Cf) connected between pairs of series devices on opposite arms of each leg of the convertor. The switches of each cell are always in complementary on/off states. As can be seen from Figure 8 the output voltage has several steps. The voltages across the floating capacitors as well as the dc capacitor (Cdc) are maintained to a constant value by switching action. In the case of the four level VSC shown in Figure 8 the voltages across the capacitors will be; Cdc = Vdc, Cf_1 = $^{2/3}$Vdc and Cf_2 = $^{1/3}$Vdc. The floating capacitors act as pseudo voltage sources so, by forcing the load current to flow through these capacitors in a particular direction, dictated by the switching states of the commutation cells, the voltage across the capacitor either subtracts or adds to the DC supply voltage. This gives four possible line-to-ground voltage states, namely $+^{1/2}$Vdc, $+^{1/6}$Vdc, $-^{1/6}$Vdc and $-^{1/2}$Vdc. The phase voltage is shown in figure 8(b).

5. The Possible Applications of VSCs in HVDC

Many HVDC schemes have been installed around the world. The following section describes some of the challenges that have been overcome using conventional technology and what changes may be brought about with the introduction of VSCs.

5.1 Rotating Machinery

Normally the ac voltage needed to turn thyristors off by natural commutation is provided by generators which already supply power to the ac network. This is the most typical application, in which HVDC transmission provides the interconnection between two distant or non-synchronised power networks (eg the 2000MW Cross Channel HVDC link between England and France). However, existing generation may not always be guaranteed, for example where one end of the HVDC link is an island load.

Small island ac networks frequently rely on diesel generators to supply ac power. HVDC may be used to connect the island to a larger ac network whose unit cost of electrical power is much less, thus making the cheaper electrical power available to the island system. To avoid having to keep diesel generators operating, just so that the HVDC convertors operate correctly, a synchronous compensator can be used to provide the necessary rotating ac voltage vector. The synchronous compensator must be designed to have sufficient inertia such that the power flow on the island is not disrupted in the event of a short disturbance to the sending end ac network.

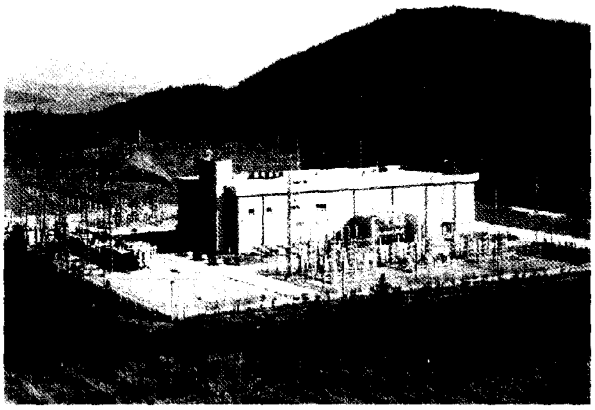


Figure 9 300 MW Convertor Station in Korea

This technique of using a HVDC scheme in conjunction with a synchronous compensator has been used on several schemes, most recently on the 2 x 150MW KEPCO HVDC project[2] which was commi-ssioned in 1997 interconnecting the mainland of South Korea to the island of Cheju. The island can be supported by two synchronous compensators and the entire island can be supplied with power from the HVDC link. The synchronous compensators are fitted with small gas turbines and clutches enabling their running costs to be minimised. In the event of a complete island black-out the synchronous compensa-tors can be started up via the gas turbines. Once the compensator is spinning the HVDC convertor can pick up the island load and the turbines can be de-clutched.

Figure 9 shows a 300 MW HVDC station in Korea, with Gas Insulated Metal Clad switchgear for filter and station switching on the left, ac filters in the foreground and the convertor transformer with its valve winding bushings protruding into the building which houses the convertor, the control and auxiliary plant.

By using VSCs to supply islanded ac loads the requirement for a synchronous compensator to supply a rotating voltage vector would be removed. The island ac frequency would be dictated wholly by the VSC, so the cost, losses and maintenance requirements of the synchronous compensator would no longer be incurred.

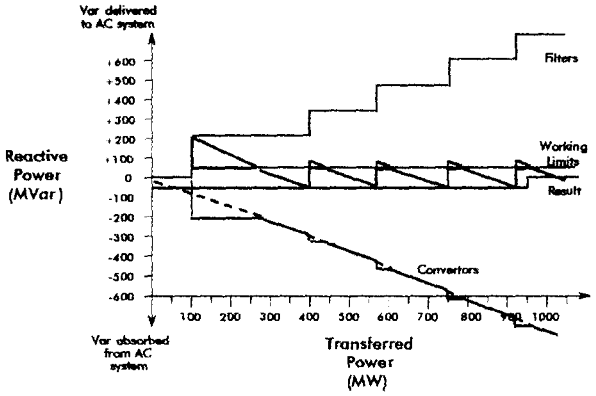


Figure 10 Control of the Reactive Power exchange with the AC system utilising the convertors to meet the working limits

5.2 Reactive Power Control

Using conventional line commutated convertors, both the sending end and the receiving end absorb reactive power. Shunt capacitors are usually used to compensate for some, or all, of the reactive power absorbed by the convertors and to give the desired power factor for the complete system. By sub-dividing the capacitor banks, reactive power can be controlled in "steps". The reactive power absorbed by the convertors is dependent on the dc operating conditions. Therefore, by manipulating these conditions the convertor absorption can be controlled which, along with the switching of capacitor banks can be used to meet tight reactive power limits for the convertor station. Figure 10 shows a graph of reactive vs real power for the Chandrapur 1000MW back-to-back HVDC interconnector.[3] Note that the line representing convertor absorption would, normally, be smooth but convertor reactive power absorption has been manipulated to meet the specified reactive power limits.

VSCs using PWM to carry out the ac/dc and dc/ac conversions allows an approximation to a sine wave to be produced by the convertor alone, having almost any desired phase relationship with an existing ac system waveform. The relative phase relationship between the two waveforms dictates the direction and magnitude of the reactive power. Therefore, switchable capacitor banks are not required but at least one fixed high frequency harmonic filter is required as the PWM technique generates high order harmonics.

5.3 Parallel Technologies

At the same time as the development of the VSC there have been developments in cable manufacturing technologies.

Extruded plastic cable manufacturing techniques are being developed, and claims are being made that such cables are cheaper than the more commonly used mass impregnated cables. However, this new cable type is sensitive to rapid voltage reversal. VSCs incorporate reverse biased diodes, preventing voltage reversal between their dc terminals, thereby potentially allowing this cable technology to be used. Voltage reversals do not normally represent a problem for mass-impregnated cables, so it has not usually been necessary to take special steps to avoid voltage reversals for conventional HVDC schemes. However, a technique developed by ALSTOM in the 1970s utilises a diode and surge arrester combination at the cable termination to control cable voltage reversals. This technique would enable the new types of extruded cable to be used with conventional line commutated convertors.

6. Advantages and Disadvantages of VSCs

VSCs can reduce the amount of electrical plant associated with an HVDC convertor station, and in particular the amount of switched reactive power/filter banks. In the case of power transmission to an islanded ac systems, VSCs can be used without any additional means of generating an ac voltage, thereby allowing all local generation to be shut down, and without having to add a synchronous compensator to the island ac system. For practical reasons the maximum voltage of a VSC convertor is, at present, limited to about ±150kVdc.

The major disadvantage of VSCs constructed using present day semi-conductors is their losses. For example, the conduction and switching losses of an IGBT are much larger than those of a thyristor of comparable rating, and several present day IGBTs are required to equal the rating of one large thyristor. Not withstanding these limitations of the VSC technology, its introduction has created a new niche market for small convertors generally below 150MW, where the technical advantages of the VSC technology fully offset any additional capital cost and cost of the power losses.

7. Conclusion

The emergence of VSCs has opened up new markets to HVDC which were previously uneconomic. The biggest present obstacle in their wider application arises from the losses of the switching devices used. However, new devices are being developed and some of these offer the prospect of potentially being able to turn off whilst still having a relatively low on-state conduction loss thereby promising to make the application of VSCs far more economically attractive.

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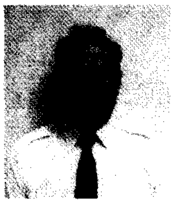

Dr. Bjarne R. Andersen

Dr. Bjarne Andersen was educated at the Technical University of Denmark, and obtained a MSc in electrical power engineering and a PhD in High Voltage Technique before joining what is now ALSTOM T&D Power Electronic Systems Ltd. (PES) as a development engineering in 1977. Apart from two periods in other parts of ALSTOM (then GEC), where he worked on Surge Arresters and Instrument Transformers, he spent the rest of his career working at various engineering levels within ALSTOM on HVDC, SVC and FACTS systems.

He is currently the Technologies Director with responsibility for Research and Technical Auditing.

He is a Fellow of the IEE. He is the Convenor of CIGRE Working Group 14-37 VSC Transmission and the UK representative on CIGRE Study Committee 14, DC Links and AC Power Electronics Equipment.