VSC Transmission Tutorial

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1. INTRODUCTION

CIGRE initiated WG B4.37 in 2001 with the objective of reviewing the VSC Transmission technology, i.e., the use of Voltage Sourced Converters for DC Transmission, in particular to evaluate issues to be considered when it is applied at voltages above 100 kVdc and at power in excess of 100 MW. Shortly after initiating the work these levels were already exceeded by equipment in commercial service, and the Working Group examined possible obstacles to reaching even higher levels.

The Technical Brochure No 269 produced by the WG provides information about the equipment included in a VSC Transmission scheme, as well as the characteristics and performance that can be expected. It is likely to be interesting to those who want to learn more about the technology, and those who want to better understand the lifetime cost issues of VSC Transmission. The Technical Brochure runs to over 150 pages, covering topics from the basic operation of VSC Transmission schemes, converter arrangements and equipment, steady state and dynamic performance to be expected, and future outlook for the technology, to the specification of a new VSC Transmission scheme.

This Tutorial is based partly on the work of WG B4.37, and partly on information and experience gained since the conclusion of the WG work.

2. BACKGROUND

HVDC Transmission has been used extensively since 1954 for the interconnection of asynchronous ac networks and for the transmission of power over long electrical distance. The converter switches now use thyristors, which are able to switch on as commanded but depend on a naturally occurring current zero for the turn off. This technology is known as line commutated converter (LCC) HVDC. The total number of LCC HVDC schemes installed by the end of 2004 had a total rating in excess of 60 GW, individual schemes having ratings between 50MW and 6300MW, and operating voltages between 10kVdc and ±600kVdc.

The use of voltage sourced converters for dc power transmission (VSC Transmission) was introduced in 1997 with the 3 MW, ±10 kVdc technology demonstrator at Hellsjön, Sweden. Subsequently, a number of commercial schemes have been installed, with the largest in service at the end of 2005 having a rating of 330 MW and ±150 kVdc.

VSC Transmission has a number of technical features that are superior to those of LCC HVDC schemes. Like LCC HVDC, a VSC Transmission scheme enables reliable and controllable power transfer between networks. Additionally, VSC Transmission converters (both rectifier and inverter) provide independent control of the reactive power at the two ends and this control is independent of the active power transfer over the dc transmission. This enables a VSC Transmission scheme to be connected to a very weak or even passive ac network, since it is self commutating and can provide ac voltage support and/or voltage reference.

3. BASIC CHARACTERISTICS OF VSC TRANSMISSION

3.1 ESSENTIAL ELEMENTS OF A VSC TRANSMISSION SCHEME

Figure 3-1 shows a simplified VSC Transmission scheme connecting two ac networks A and B. The essential elements of the VSC Transmission scheme are:

- The converters VSC A and VSC B, which perform the conversion between the dc voltage and the ac voltage.

- The dc capacitors, which provide the voltage source, from which the ac voltage is created by switching of the converter.
- The transmission link, which enables energy to be exchanged between the dc capacitors at VSC A and VSC B.
- The inductive impedance between the converter and the ac network, which enables the active and reactive power to be controlled.

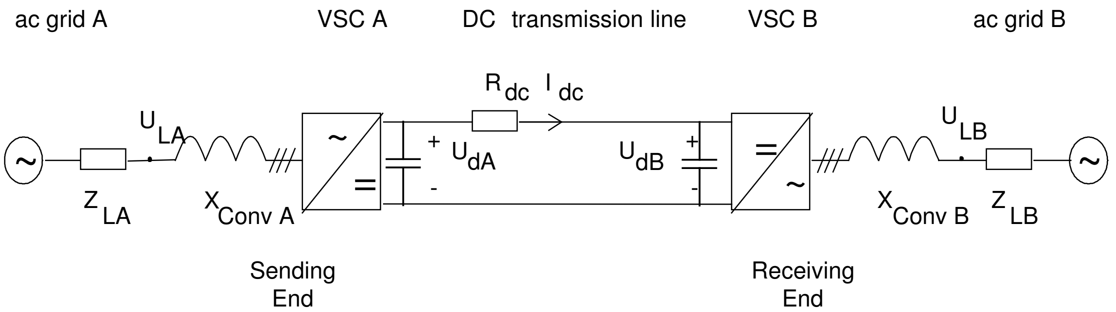

Figure 3-1
Simplified diagram of a VSC Transmission scheme

3.2 THE DC TO AC CONVERSION PROCESS

A VSC has a capacitor connected directly across its dc terminals. For short-time transients, the capacitor represents a dc voltage source. The switching devices connect the dc and ac terminals in a time sequence such that a high-frequency square wave voltage is produced. The square wave voltage contains the useful fundamental frequency voltage, as well as a number of harmonics, which are removed by filtering. The simplest converter implementation is a 2 level converter as shown in Figure 3-2.

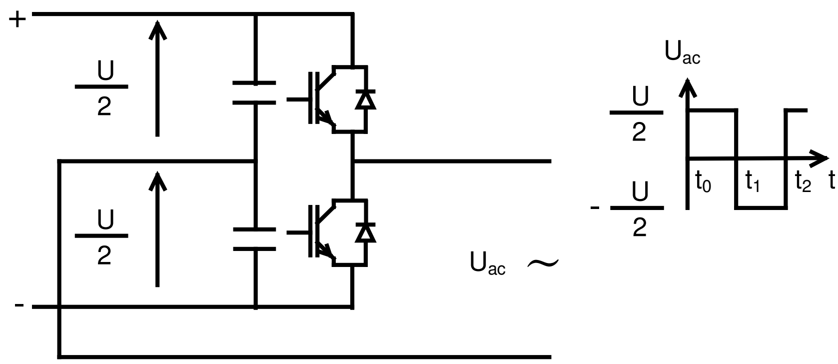

Figure 3-2
Single Phase 2-level converter with switching output shown

Assuming both IGBTs are blocked (i.e. the IGBTs are in the high impedance state) the freewheeling diodes form an uncontrolled rectifier. An external ac voltage source applied as U_{ac} would charge the two dc capacitors via this rectifier to the peak value of the ac voltage $U_{dc}/2 = U_{ac}$ across the upper and lower dc capacitor, with polarities as shown in the figure. With the dc capacitors charged and the external source connected, the VSC is ready for operation.

The IGBTs can be switched on and off in a desired pattern via the gate signals. Switching on the upper VSC valve at time t_1 changes the ac output from U/2 to –U/2, and switching on the lower valve at time t_2 changes the ac output from -U/2 to +U/2.

The ac output voltage can only attain two different amplitudes, namely +U/2 or –U/2. The diode connected in parallel to the IGBT prevents the direct voltage from changing polarity, since the diode would enter into conduction, if the polarity were to change such that the diode became forward biased, thereby discharging the dc circuit. The current can however flow in both directions through the VSC valve, passing through either the IGBT or the diode. This characteristic is one of the main differences between VSC Transmission and LCC HVDC

During operation, only one of the two IGBTs is in the conductive state and the other is turned off. Turning on both IGBTs at the same time would create a short circuit of the dc capacitors, and must be prevented. In order to avoid such a short circuit, the IGBT in the off-state is turned on shortly after the IGBT in the on-state is turned off. The short instant (about 10 microseconds), during which neither of the IGBTs are on, is called the "blanking time", and during this time the current path is provided by the freewheeling diodes.

Assuming the upper IGBT is turned on at t = 0, as shown in Figure 3-2, the ac terminal would be connected to the positive terminal of the storage capacitor, resulting in current flow through the upper IGBT. Depending on the pulse pattern applied, the upper IGBT will be turned off after a short time span at t = t1. However, the source impedance of the external ac circuit, which in most cases will be the impedance of the interface transformer and/or converter reactor, will maintain the present current. Thus, the diode connected in parallel to the lower switch turns on. As a consequence, the voltage U_{ac} changes from plus to minus U/2. The polarity reversal is initiated by turning off the IGBT actively, i.e., while it carries current.

The lower IGBT is required to be on whenever the current reverses, to maintain the voltage polarity, and therefore it will get a gate signal following the blanking time. The IGBT will then take over current as soon as the current reverses its direction, the timing of which depends on the impedance of the interface transformer and the converter reactor, as well as on the ac system voltage.

If current is still flowing in the diode parallel to the lower switch, when at t = t2 it is required to connect the converter ac terminal to the positive terminal of the VSC dc capacitor again, then it is necessary to first ensure that the lower IGBT is turned off. Therefore, the lower IGBT is turned off and the blanking time is allowed to pass, before the upper IGBT is turned on. During the blanking period the current continues to flow through the diode. When the upper IGBT is switched on, a temporary current path from the VSC dc capacitors through the upper IGBT and the lower diode back to the VSC dc capacitors is created. The current flowing in this circuit will extinguish the current in the diode, which will automatically turn off, leaving the upper IGBT as the only current-carrying device, and causing the desired voltage polarity reversal at U_{ac}.

In principle it would be possible to switch each valve on and off just once per power frequency cycle to perform the conversion between dc and ac. However, whilst it would be possible to control the phase angle of the fundamental frequency component of the resulting waveform, there would be a fixed ratio between the dc and the ac converter voltage. Thus, in order to control the reactive power, without the use of a tapchanger, it would be necessary to change the dc voltage, which is not desirable on a transmission scheme. Additionally, the ac harmonics would be very large.

By switching the valves on and off several times each power frequency cycle, additional degrees of freedom are available for the controls. Thus it becomes possible to control both the amplitude and the phase angle of the fundamental frequency component of the ac voltage, independently of the dc voltage, subject to the limitation caused by the dc voltage. Additionally, by increasing the switching frequency, harmonics in the lower frequency range (typically below the switching frequency) can be reduced or nearly eliminated. As a consequence harmonics in the higher frequency range increase but filtering of these can be achieved more easily. However, increasing the switching frequency also increases the power loss. Therefore, an optimisation has to take place to balance the harmonic level, on the one hand, and the capital cost, power loss, site area, etc., on the other.

Many different control strategies can be used for converters switched more frequently than once per cycle. Figure 3-3 shows the derivation of the switching instants for a control methodology using a triangular carrier wave ($V_{carrier}$) and a pure sine wave ac voltage reference ($V_{control}$). The figure shows the derivation of the control signals (a), and the resulting waveshape (b).

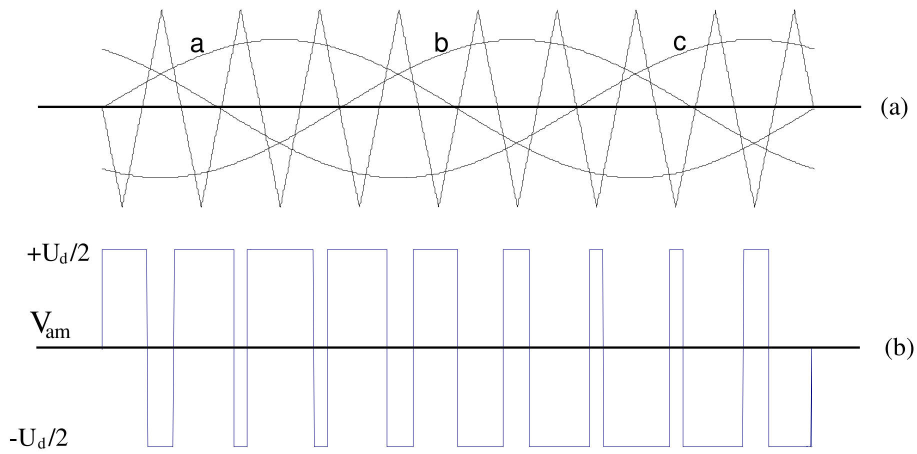

Figure 3-3
PWM controlled VSC with pure sinewave ac voltage reference and triangular carrier

The intersection between the carrier triangles and the sine wave determines the switching time for the VSC valves. When $V_{control}$ is greater than $V_{carrier}$ the converter output is positive, and when $V_{control}$ is smaller than $V_{carrier}$ the converter output is negative. The ratio between $V_{control}$ and $V_{carrier}$ is known as the modulation index m.

$$m = \frac{Vcontrol}{Vcarrier}$$

The value of the modulation index can be chosen to any value between 0 and 1. The fundamental frequency component of the VSC ac voltage varies linearly with the modulation index, with a maximum voltage equal to the dc voltage.

In the example shown in Figure 3-3, the frequency of the carrier wave is 9 times the power frequency. If the carrier frequency is an odd integer multiple of the fundamental frequency the ac waveform does not contain any even harmonics. In a three-phase VSC all of the triplen harmonics, i.e. 3^{rd,} 9th, etc are eliminated in the phase to phase voltages. Both of these statements assume that the ac network is balanced and free of background harmonic distortion.

3.3 ACTIVE AND REACTIVE POWER CONTROL

The voltage sourced converter (VSC) can be considered equivalent to a synchronous generator without inertia, and has the capability of controlling active and reactive power at its terminals. The exchange of active and reactive power between a VSC and the ac grid is controlled by the phase angle and amplitude of the VSC output voltage in relation to the voltage of the ac grid.

Figure 3-4 illustrates the control of active power through the converter line inductance by the variation of the phase angle. When the phase angle of the converter ac voltage U_{conv} leads the ac system system voltage U_L the VSC injects active power in the ac system. Conversely, when the converter ac voltage lags behind the ac system voltage the VSC absorbs active power from the ac system.

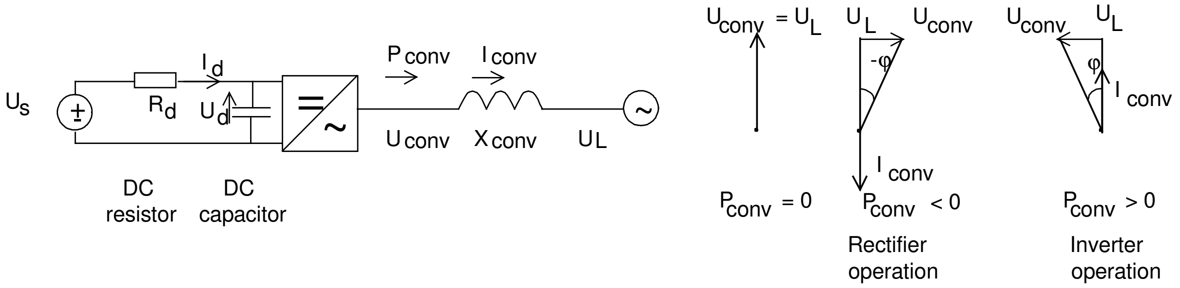

Figure 3-4
Active Power Control

Similarly, Figure 3-5 illustrates the control of reactive power. When the amplitude of the converter ac voltage U_{conv} is larger than the ac system voltage U_L ,the VSC injects reactive power in the ac system, i.e. it acts as a shunt capacitor. Conversely, when the converter ac voltage is lower than the ac system voltage the VSC absorbs reactive power from the ac system, i.e. it acts as a shunt inductor.

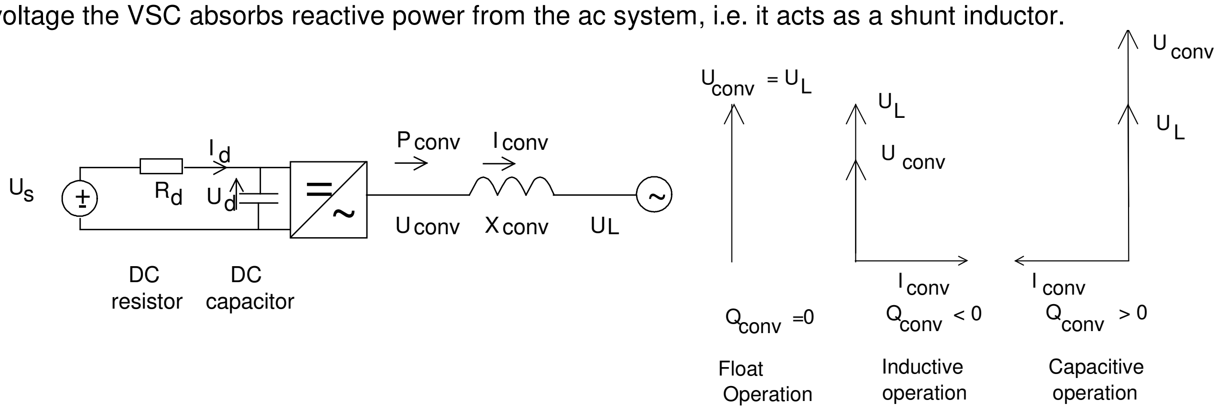

Figure 3-5
Reactive Power control

Both the amplitude and phase angle of the VSC ac voltages can be controlled independently of each other, subject to possible rating limitation in the converter and the balance of active power of the converters at the two ends. Thus, the active and reactive power output of the converter can be controlled to provide active power transmission as well as independent reactive power control at the terminals.

3.4 ACTIVE AND REACTIVE POWER CAPABILITY

A simplified steady state operating range of one of the terminals in a VSC Transmission scheme, expressed as the VA capability at its ac connection point, is illustrated in Figure 3-6. The figure has been drawn for 3 different ac network voltages, to illustrate the dependence of the capability on the ac voltage. The use of a tapchanger on the interface transformer can remove this dependence for steady state operation, thereby enabling the capability of the converter to be utilized more fully.

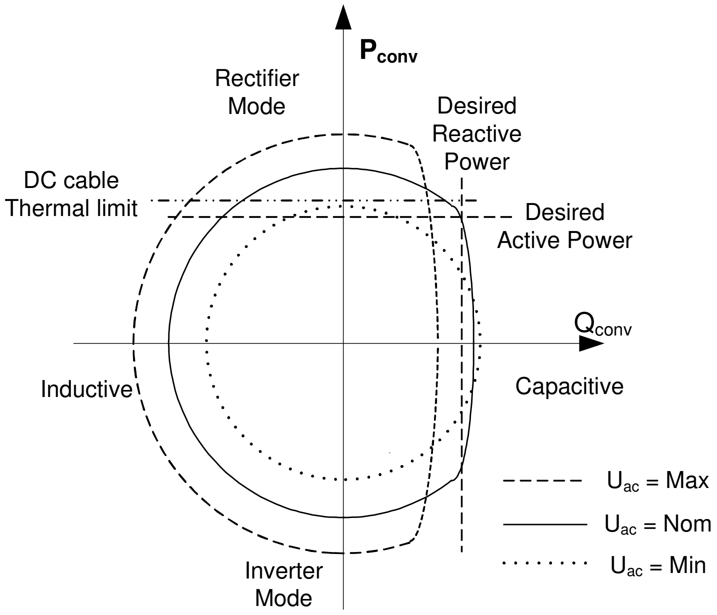

Figure 3-6
Simplified PQ characteristic of a VSC Transmission terminal

The maximum current capability of the VSC Valve dictates the MVA capability at a given ac voltage. Assuming that the IGBT and the diode have the same current capability, the MVA capability at a given ac voltage can be assumed to be described by a circle. The thermal duty on the IGBT consists of the switching loss and the conduction loss. The switching loss exceeds the conduction loss when the IGBT is operated at a relatively high switching frequency. For the diode the switching loss tends to be much smaller than the conduction loss.

In the example shown in Figure 3-6, the active power capability of the VSC Transmission scheme exceeds the desired capability at all ac voltages within the range of U_{min} to U_{max}.

The voltage on the dc capacitors and dc cables must be kept low enough to provide safe operation for the VSC valve, the dc capacitor and the cable. The ac voltage produced by the converter depends on the direct voltage on the dc capacitor. This then results in a limitation on the capacitive reactive power, which the converter can produce. Since the generation of reactive power requires the converter voltage amplitude to be higher than the ac network voltage, the capacitive power capability falls with increasing ac voltage. In the example shown in Figure 3-6 the capacitive power capability is lower than the desired output at the maximum ac network voltage. In practice this is likely to be acceptable, since generation of reactive power is unlikely to be required when the ac network voltage is already higher than the nominal value. When specifying the required reactive power capability, it is necessary to state explicitly the ac voltage and active power exchange at which the reactive power capability is required.

The dc cable may impose a restriction on the maximum dc current amplitude between the VSC Transmission terminals. This limitation will typically be just above the desired power transfer capability, and the VSC control system will ensure that this limit is not exceeded. For clarity the dc cable limit in Figure 3-6 is shown significantly higher than the desired power transfer capability.

4. COMPARISON OF LCC HVDC AND VSC TRANSMISSION

VSC Transmission and LCC HVDC Transmission is compared in the table below:

LCC HVDC	VSC Transmission
The power semi-conductor used in today's LCC HVDC schemes is the thyristor, which can be triggered into conduction by a low power gate signal when the device is forward biased, and which will turn off when the current through the device attempts to reverse. The power rating of thyristors used for LCC HVDC schemes is very large, with individual devices having a capability of 8.5kV withstand voltage and 4kA current capability. Since the thyristor can withstand voltage in both directions, the dc voltage can be reversed. When changing the direction of power flow between the two terminals in a LCC HVDC scheme, the polarity of the direct voltage is changed, since the thyristors can conduct current only in one direction. LCC HVDC is not normally able to operate continuously at a direct current below about 5% of the rated current, because the harmonics results in discontinuous current operation	VSCs use semi-conductors, with turn-off as well as turn-on capability, and high speed switching capability. The semi-conductor used today in Voltage Sourced Converter applications is the insulated gate bipolar transistor (IGBT). The maximum device rating commercially available at the end of 2005 is 6500V and a current capability of up to 2kA. The IGBT is capable of withstanding voltage only in the reverse direction, and a diode is used in parallel to the IGBT to prevent the voltage reversal. The diode also enables direct current to flow in the opposite direction. When changing the direction of power flow between the two terminals in a VSC Transmission scheme the direction of direct current flow is reversed. The direction of power flow can be smoothly changed through zero, and there is no constraint on the duration of operation at any power within the rating of the converters.
The Line Commutated Converter as used in LCC HVDC is normally a Current Sourced Converter (CSC). An ideal CSC has a constant direct current at its dc terminals and creates an alternating current at its ac terminals by the switching of the converter.	VSC Transmission is based on the use of Voltage Sourced Converters (VSC). An ideal VSC has a constant dc voltage at its dc terminals, and creates an alternating voltage at its ac terminals by the switching of the converter.
A typical LCC HVDC scheme operates with a lagging power factor, absorbing reactive power equivalent to approximately 50% of the active power, and therefore can only be operated in 2 quadrants of the PQ diagram. AC harmonic filters and shunt capacitors are used to offset the converter's reactive power absorption, such that the overall power factor is acceptable to the ac network. The ac harmonic filters and shunt capacitors are normally switched in and out by means of circuit breakers as the dc load varies.	The VSC can be operated in all 4 quadrants of the P and Q diagram, with the active and the reactive power flow at the converter ac terminals controlled in accordance with operational requirements. The high switching speed capability of the VSC valves in a VSC makes it possible to switch each valve on and off several times in each power frequency cycle. This feature can be used to significantly reduce the low order harmonic content of the voltage on the ac and the dc side of the VSC, making it unnecessary to use breaker switched ac harmonic filters.
The site area of LCC HVDC scheme is dictated largely by the ac harmonic filters and the ac switchyard necessary for the switching of these to achieve an acceptable power factor during operation.	This site area of a VSC Transmission terminal is dictated largely by the size of the converter, which tends to be of similar size to that of an LCC HVDC converter. Typically a VSC Transmission scheme occupy 40% or less of the area required for a LCC HVDC terminal.

LCC HVDC	VSC Transmission
As a typical LCC HVDC scheme can only influence the ac voltage by filter and tapchanger switching, the short circuit level of the ac system at the point of connection must be reasonably strong, in order to achieve acceptable performance during dynamic and transient conditions. For a conventional LCC HVDC transmission scheme, the minimum short circuit level typically needs to be about 3 times the rating of the HVDC scheme. By arranging the converter control characteristics, such that a drop in ac voltage results in a reduction in reactive power absorption and vice versa, it becomes possible for the converter to operate satisfactorily at lower short circuit level at one of the terminals.	As a VSC Transmission scheme can provide reactive power support at both terminals independently of the active power transmitted, it can stabilise the ac network voltage, and a minimum short circuit level at the point of connection is not required. As a consequence, a VSC Transmission scheme can be used to interconnect networks, even when both networks are weak.
The large breaker switched ac harmonic filters and shunt capacitor banks required for steady state ac voltage control in an LCC HVDC scheme can result in substantial temporary over-voltages during events where power transmission suddenly stops, e.g. during dc line faults or converter faults.	A VSC Transmission scheme typically uses a fixed ac harmonic filter, and the converter is rated to provide the varying reactive power requirements for the envisaged operating conditions. Since the filter is relatively small, and the healthy converter can continue to control reactive power without circulation of direct current, the ac over-voltage caused in the event of a sudden stop in power transmission is typically very small.
In the event of a sudden drop or phase shift in the ac voltage amplitude, the LCC converter may not be able to complete the commutation of the inverter before the voltage across the outgoing valve becomes forward biased, and therefore the valve will continue to conduct. As the valves continue to be fired, a short circuit between the dc terminals of the 6-pulse bridge will be caused. This event is called a commutation failure, and results in a temporary dc over-current, which is quickly reduced by control at the rectifier. Typically normal commutation and power transmission can be restored within two power frequency cycles, and the event has no significant impact on the operation of the ac system.	Since the VSC valves can be turned off as well as being turned on, the operation of a VSC Transmission scheme is not significantly influenced by voltage dips or other transients ac disturbances. In particular, a VSC Transmission scheme does not suffer commutation failures.
In the event of a short circuit on the dc side of a LCC HVDC scheme, the converters can quickly stop the current flowing into the fault, merely by stopping the firing of the thyristor valves. The quick reaction of the converter control and protection will minimize any damage caused by the fault. If the fault is on a dc overhead line, then the power transmission is stopped for a sufficient period of time to allow de-ionization of the arc, typically 200-300ms, and transmission is then resumed. Several re-start attempts, with increasing de-ionization periods, can be used if desired.	The diodes in the VSC would conduct current into a fault on the dc side, even when the IGBTs are turned off. Therefore, the ac breakers at both ends of the VSC Transmission scheme must be opened in the event of a fault on the dc line. The scheme then has to be re-started once the fault has been removed. All commercial VSC Transmission schemes have so far used cables rather than overhead lines, which reduces the number of faults on the dc side.
The power loss is typically 1.6% for two LCC HVDC converter stations at full power.	The power loss is typically 3.8% for the two VSC Transmission stations at full power.

The advantages and disadvantages of VSC Transmission compared with LCC HVDC can be summarised as follows:

4.1 VSC ADVANTAGES COMPARED WITH LCC

- Commutation failures due to grid fault or ac voltage dips do not occur.
- The VSC may be operated at a very small short-circuit ratio, and can even energise a passive or dead grid (black start capability).
- VSC Transmission has no minimum dc current limits.
- Reactive power at each terminal can be controlled independently of the active power within the rating of the equipment.
- Harmonic filters need not be switchable.
- Voltage polarity on the dc side is always the same allowing a more economic cable design.
- VSC stations can be designed to eliminate flicker and selected harmonics in the ac grid.
- VSC stations can be operated as STATCOMs when not connected to the dc line.
- The footprint of a VSC station is considerably smaller than that of an LCC HVDC station.
- Inherently, VSC Transmission can operate without telecommunication between the VSC substations.

4.2 VSC TRANSMISSION DISADVANTAGES COMPARED WITH LCC HVDC

- Power losses are considerably higher.
- The current (end 2005) maximum VSC Transmission ratings are ±150 kV and 350 MVA (receiving end).
- Practical experience with VSC Transmission is not as extensive.
- VSC Transmission is not currently designed for operation with dc overhead lines.

Today, the main obstacles to VSC Transmission are its high power losses and its inability to use dc overhead lines, which makes it less suitable for long distance overland bulk power transmission.

5. VSC TRANSMISSION APPLICATIONS

HVDC transmission has been used since its first introduction in 1954 to provide interconnections between ac networks and the transmission of bulk energy over long distances. The benefits arising from the use of HVDC as an interconnector include:

- The power flow on the interconnector is fully controlled. This feature means that loop power flows can be avoided.
- It is possible to interconnect asynchronous networks.
- When the interconnector electrical distance is very long, e.g. >800km overland or >70km submarine, HVDC transmission may provide a more economic solution, both in terms of capital cost and power loss.

VSC Transmission can be used in all the applications for which LCC HVDC are currently used. The reactive power control capability of a VSC Transmission scheme means that it is better suited to applications with passive or very weak ac networks, than a LCC HVDC solution.

5.1 INTERCONNECTION TO A SMALL ISOLATED NETWORK

Communities in remote areas, or on small islands, may rely on diesel generation for their electricity supply. The cost of provision of electrical energy in such locations may be very high, because advantage cannot be taken of the benefits of large-scale generation available in the main networks. Additionally, generation of the energy using small diesel generators is more damaging to the environment, than when using large-scale generation in a major network, with its more efficient generators and operating modes. Therefore, transmission of energy from the main network may be economically and environmentally attractive.

VSC Transmission may offer a good solution to such power transmission if overhead line or submarine ac transmission is not feasible, e.g. if the distance is large, or if an underground cable solution is considered advantageous.

VSC Transmission is advantageous compared to a LCC HVDC solution for the supply of power to an isolated/passive network, because synchronous compensators are not necessary for the operation of the VSC. This means that significantly less maintenance will be required, not only because the VSC solution has fewer components than a LCC HVDC scheme, but also because of the omission of a rotating machine. Additionally, whilst the power loss of a VSC Transmission scheme can be 2 or 3 times higher than that of a LCC HVDC scheme, the difference would be reduced in this application by the relatively large power loss associated with the operation of a synchronous compensator, which would be necessary, when using LCC HVDC..

5.2 INTERCONNECTION BETWEEN WEAK POWER SYSTEMS

For weak ac network applications the control of the ac network voltage is particularly important. When a LCC HVDC scheme is used, the large ac harmonic filters and shunt capacitors used to provide reactive power compensation actually reduce the ac voltage stability of the system, since the reactive power support reduces as the ac voltage reduces. Therefore, the application of LCC HVDC schemes is typically limited to systems where the short circuit power at the point of connection of the LCC HVDC terminal is at least 3 times the rating of the scheme. Special control methods can be used when operating at lower short circuit level, but these typically require a higher rating of the converter station equipment. Alternatively, additional reactive power support, in the form of SVCs or STATCOMs, can be applied at the point of connection, to improve the ac voltage stability.

As a VSC Transmission scheme is capable of controlling the reactive power at its ac terminals independently of the real power flow between terminals (subject to overall rating limitations), it provides a good solution for the interconnection of networks, where the ac network at one or both terminals is weak.

5.3 REINFORCEMENT OF WEAK AC TIE-LINES FOR STABILITY IMPROVEMENT

When an ac transmission line is imbedded in a geographically large ac network with major load and generation centres at its extremities, a fault within either of the centres can cause major power oscillations on the ac tie line. If the tie line is weak (e.g. because of its length or because of its rating relative to the network), then the power oscillations may exceed the over-current setting of the line protection, resulting in a trip of the line. The power oscillations may also have a significant impact on the ac voltage along the line and at the termination points.

The power oscillations can be damped by the insertion of controlled series compensation, or, less effectively, by the use of controlled shunt reactive power compensation. A more effective solution would be the installation of a parallel VSC Transmission scheme. Studies have shown that a VSC Transmission scheme can increase the stability limit on a weak ac tie line by more than the rating of the VSC Transmission scheme, by suitable modulation of the real power transfer of the VSC Transmission scheme AND the reactive power at its terminals.

5.4 CONNECTION OF DISTANT LOADS (OFF-SHORE OIL AND GAS PLATFORMS)

As an oil or gas reservoir is emptied, the power required to extract and transport the oil or gas increases. Where the production platform is located off shore, and at significant distance from the coast, the electrical power required for the operation has typically been produced by diesel or gas turbine generators located on the production platform. However, as the power requirement increases, additional generating plant becomes necessary and consideration may be given to obtaining the electrical power from the on-shore ac network. The advantages of obtaining the power from the shore include:

- Manpower intensive generation plant on the platform can be removed.
- CO_2 emissions are reduced since the efficiency of on-shore generation plant is more efficient, and may include renewable generation plant.

When the distance to the shore is large, transmission by means of ac may not be feasible, and HVDC transmission may be considered. The use of VSC Transmission provides the following advantages:

- The VSC Transmission equipment is compact, making the installation on existing platforms feasible.
- There is no need for synchronous compensators since the VSC Transmission scheme is self-commutating, and controlled reactive power can be provided, independently of the active power being transmitted.
- The VSC Transmission scheme can provide variable frequency power supply to the offshore motors, acting as a variable speed motor drive.

5.5 CONNECTION OF REMOTE WIND-PARKS

Wind generation is currently one of the most economical sources of renewable generation, and is the fastest growing sector of electrical power generation. As more and more wind generators are installed there is a tendency for the wind farms to be located further away from population centres, partly because of better wind conditions and partly to reduce the visibility of and audible noise from the wind turbines. Wind conditions are often best in offshore locations and many new offshore wind farms with ratings of 500MW and more are under consideration in several countries.

Whilst a HVDC terminal occupies more space and costs significantly more than an equivalently rated ac substation, HVDC Transmission provides the following advantages:

- The transmission distance can be much larger, enabling connection at a more suitable point in the ac network.
- The HVDC scheme will provide de-coupling between the main ac network and the wind farm network, improving the ride through capability of the wind farm during faults in the mainland ac network.
- The frequency of the offshore network can be allowed to vary with the speed of the wind, increasing the efficiency of the wind farm.

In addition to these general advantages, a VSC Transmission scheme provides the following advantages compared with a LCC HVDC scheme:

- Connection can be made to a weak point in the ac network.
- The VSC Transmission scheme can provide reactive power support of the wind farm ac network, improving the power quality and stability of the wind farm ac network.
- Flicker caused by operation of the wind farm will not be transmitted to the mainland ac network.
- Power can be transmitted to the wind farm ac network during conditions of little or no wind, to satisfy the auxiliary power requirements for both the VSC Transmission scheme and for the wind generators.

The optimum overall design of the wind farm and interconnector would be achieved when taking into account the technical capability of the wind generators and the VSC Transmission scheme.

6. COMPONENTS OF A VSC TRANSMISSION SCHEME

Figure 6-1 shows the basic structure of a VSC Transmission substation and the location of the major power components. The functions and important design aspects of each component are explained in CIGRE Brochure 269, and are briefly outlined below.

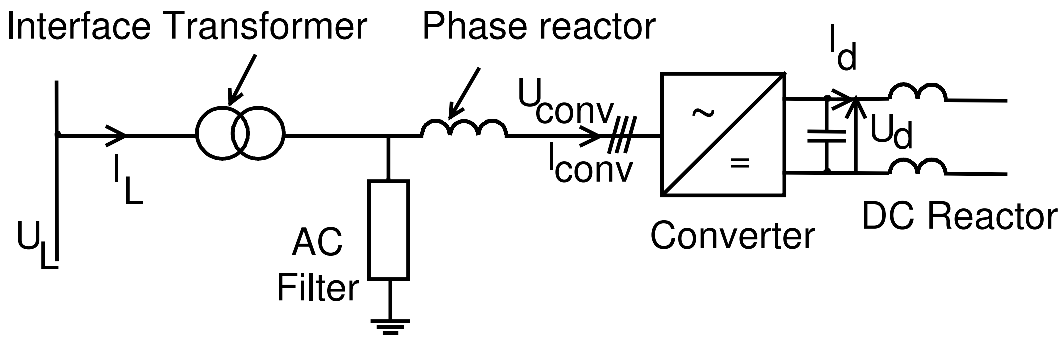

Figure 6-1 Simplified diagram of a VSC Transmission substation

6.1 CONVERTER ARRANGEMENT

The Voltage Sourced Converter performs the conversion between ac and dc and vice versa. For short-time transients the dc capacitor at the dc terminals of the converter can be regarded as a constant voltage source. The switching devices interconnect the dc terminals and the ac terminals using a control sequence resulting in an alternating ac waveform at the ac terminals, with a desired fundamental frequency amplitude and phase angle.

The simplest converter implementation is a 2-level converter as described in section 3.2 and shown in Figure 3-2. In the 2-level VSC the ac voltage at the converter ac terminals can attain only the voltage at the two dc terminals. By using PWM control, the 2-level converter is able to control active power with a constant dc voltage, and also to move the harmonics to higher orders, which are easier to filter.

By subdividing the dc capacitor and the VSC valves it is possible to arrange for the ac voltage at the VSC terminals to move not only to the voltage at the two dc terminals but also to intermediate levels. The number of voltage levels to which the ac terminal voltage can be switched will depend on the number of valves and the number of dc capacitor subdivisions or additional dc capacitors. These arrangements are known as 3-level or multi-level converters, depending on the number of voltage levels that can be achieved.

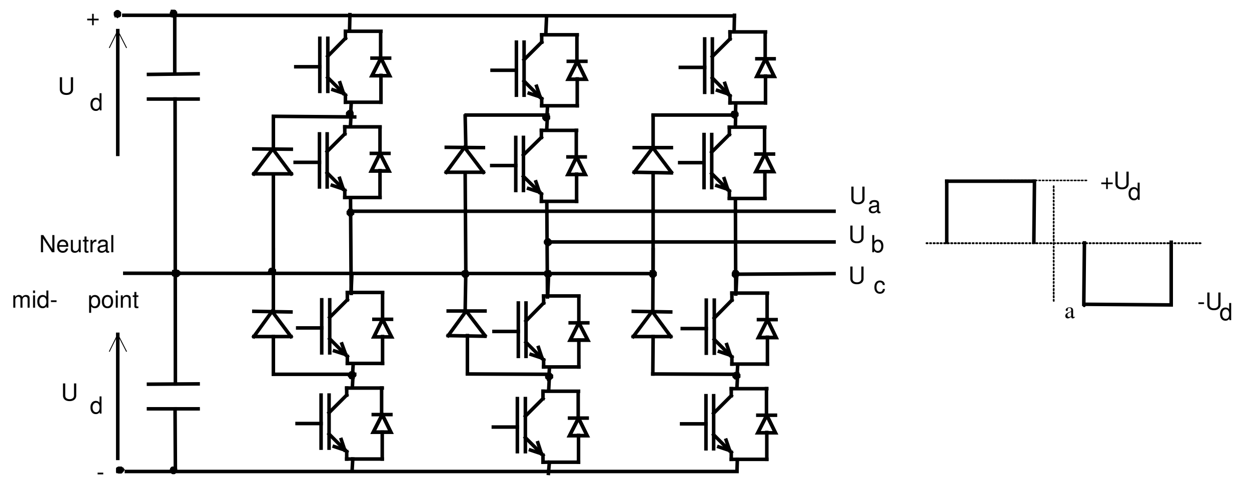

Figure 6-2
Three-phase, 3-level converter with full wave switching

Figure 6-2 shows a Three-phase, 3-level VSC implemented with a Neutral Point Clamped (NPC) topology. The converter has three dc terminals connected to a centre-tapped dc source. The converter has 12 valves and 6 diodes connect to the dc supply centre-tap, which is the reference zero potential. With identical valve terminal-to-terminal voltage rating, the total dc supply voltage can be doubled.

The ac waveform shown in Figure 6-2 is the phase-to-neutral voltage, assuming fundamental frequency switching of the valves. The output voltage of the 3-level phase unit can be positive, negative, or zero. Gating on both upper valves in a phase unit produces positive output, while gating on both lower valves produces negative output. Zero output is produced when the upper and the lower middle valves are gated on, connecting the centre tap of the dc supply via the two diodes to the output. At zero output, positive current is conducted by the upper-middle IGBT and the upper centre-tap diode, and negative current by the lower-middle IGBT and the lower centre-tap diode.

The magnitude of the fundamental frequency component of the output voltage produced by the phase unit is a function of α. When α equals zero degrees it is maximum, while at α equals 90 degrees it is zero. Thus, one advantage of the 3-level phase unit is that it has an internal capability to control the magnitude of the output voltage without changing the number of valve switching operations per cycle.

PWM control can also be used with a 3-level or multi-level converter, making it possible to control the fundamental frequency component of the ac voltage, and to reduce low order harmonics.

6.2 VSC VALVES

The VSC Valves must be capable of switching on and off in response to control signals, irrespective of the current flowing though the valve, or of the voltage across the valve, at the time of the switch operation. The VSC Valves use Insulated Gate Bipolar Transistor (IGBT) for the following reasons:

- The converter can be turned off even in short circuit conditions.
- It is possible to actively control the voltage across the device, which is useful for the sharing of voltage between a large number of series connected devices.
- Control of the device is achieved using low-power, which is advantageous when operating at very high voltage levels.
- It is capable of high switching speed.

Each VSC valve includes a few redundant devices to enable continued operation in case of failure of an individual component. Therefore, a faulty device must enter into a safe short-circuit mode and be capable of conducting current until it can be changed out, e.g. during a scheduled maintenance period. To meet this objective, specially developed IGBT press-pack designs are used for VSC Transmission and other high-voltage applications.

The voltage sharing across the series connected devices in a VSC Valve during turn off and in the off state can be controlled using the IGBT's transistor action. The IGBT is designed to have forward voltage blocking capability only, since a parallel diode provides current capability in the reverse direction, and this diode provides protection against reverse voltage. High blocking speed diodes, with low recovered charge, are used in order to minimise power losses.

Figure 6-3 shows VSC valves inside a valve enclosure. A single valve for a ±150kVdc, 2-level, VSC Transmission scheme, can contain more than 300 series connected IGBTs. The enclosure is made of steel and aluminium, and acts to contain the electromagnetic interference caused by the switching of the VCS Valves. For some applications the enclosures can be implemented as transportable containers, such that a significant part of the checking and testing can be done in the factory, before the valve enclosures are sent to site.

Figure 6-3
VSC valves inside Valve Enclosure.

6.3 DC CAPACITOR

The dc capacitor provides the voltage source for the operation of the VSC. The dc capacitor also plays an important part in the harmonic filtering on the dc side. The dc capacitor is connected directly across the converter dc terminals, and recent VSC Transmission schemes have used dry type dc capacitors, to eliminate the risk of fire.

The dc capacitors are located very close to the VSC valves to minimise stray inductance in the commutation circuit, which causes a voltage stress at each commutation. As the direct voltage increases, the necessary insulation clearances increase dis-proportionally. At the same time, there will be more series-connected IGBTs to share the increased voltage stress. When higher dc voltages are used, it may be necessary to improve the design techniques or use snubber circuits to achieve the satisfactory series connection of devices. While there appears to be no technical limitation to the dc voltage that can be achieved for a VSC Transmission scheme, it is likely that as the dc voltage increases the power losses and capital costs will increase more than proportionally.

The high frequency current in the dc capacitor causes electromagnetic noise, which must be contained as it cannot be eliminated at source (the high frequency current is necessary for the operation of the converter). Typically, the dc capacitor is mounted inside the shielded valve enclosure as close as possible to the VSC valves.

The flow of current causes a change of the voltage across the dc capacitor, and this change is known as the voltage ripple. The amplitude of the voltage ripple depends on:

- The capacitance of the dc capacitor - the larger the capacitance the smaller the ripple.
- The VSC Valve switching strategy - long conduction periods at high current cause larger ripple.

6.4 CONVERTER REACTOR

The converter reactor performs the following important roles:

- It provides constant fundamental frequency impedance for the control of the VSC active and reactive power output.
- It provides a high frequency blocking filter between the VSC and the ac network.
- It limits short circuit currents.

Typically, the converter reactor has a short-circuit impedance of about 15%. The converter reactor must also have very low stray capacitance between its terminals, since high frequency current might otherwise bypass the reactor. The need for low stray capacitance makes the air-cored and air-insulated design particularly attractive.

The reactor can be very large, and is typically enclosed in a metallic shield, to prevent the escape of magnetic fields. Forced air circulation is used to cool the reactor. Because of the duty as a high frequency blocking filter, the reactor is continuously exposed to the voltage steps in the ac output voltage. The reactor design must take this stress into account, to ensure that the reactor will perform satisfactorily throughout the life of the VSC Transmission scheme.

6.5 INTERFACE TRANSFORMER

A transformer may be used to couple the converter ac filter bus and the ac network. The use of a transformer fulfils the following tasks:

- It enables the VSC to be designed independently of the ac network voltage constraints. If the transformer has an online tapchanger, it is possible to adjust the voltage on the converter side of the transformer independently of the ac network voltage, to achieve optimum converter performance and reduction of the steady state power loss.
- It blocks the flow of zero sequence current between the ac network and the converter.
- It provides additional series impedance on the ac side, which may be beneficial for the harmonic performance of the converter, and may enable a reduction in the rating of the converter reactor.

Since the interface transformer is not exposed to direct voltage, and the harmonic filtering is performed on the converter side of the transformer, a conventional station transformer can be used. A tertiary winding can be provided for the connection of the auxiliary supply system.

6.6 DC CABLES

The transmission of energy between the VSC Transmission terminals is achieved by dc cables. In principle, when the transmission is over land, it could also be achieved using an overhead dc line. However, a fault on the dc side requires tripping of the ac circuit breakers at all terminals to clear the fault. Therefore, at present all commercial VSC Transmission schemes use dc cables.
The use of dc cables has a number of advantages compared to the use of dc overhead lines:

- Cables often have less environmental impact than an overhead line.
- The right of way required for a cable installation is considerably less than that for an overhead line, and the land above the installed cable can often be returned to its previous use.
- Cables can be run next to roads and through existing tunnels.
- Cables are much less prone to faults than overhead lines. In particular, lightning strikes or pollution do not affect a cable.

The voltage polarity on a dc cable in a VSC Transmission scheme is fixed and independent of the power direction. This enables the use of XLPE type polymeric cables to be used for VSC Transmission. Polymeric cables can be lighter and have smaller bending radii than conventional oil-impregnated or oil-filled cables, which must be used with LCC HVDC schemes. Therefore, polymeric land cables are easier to handle during installation, and special direct ploughing and laying techniques can be used where the ground conditions are favourable, making installation less time consuming. An additional advantage of the use of polymeric cable is that environmental risks are lower than with an oil-impregnated or oil-filled cable.

7. SYSTEM ISSUES

The control of a VSC Transmission scheme is similar to the control of a LCC scheme except that techniques from variable speed drives are used for the determination of firing instants. In case of external temporary faults in the ac grid, the VSC scheme may have to stop power transmission until the fault has been cleared. Once the temporary external ac fault has been cleared, the VSC will restart and recover its transmission automatically. So far all commercial applications have used dc cables, so all dc side faults are treated as permanent.

When VSC Transmission supplies power to an isolated network, the protection philosophy has to be reviewed, because the short circuit current is so close to the nominal current that classical protection relays (overcurrent detection) might be prevented from operating correctly. In such cases, the VSC scheme may be designed to feed larger currents to ac faults in order to make classical protection relays operate.

Normally, simple models are adequate for VSC Transmission system modelling for feasibility studies and project development. The technical characteristics and fast controllability of a VSC Transmission scheme make it useful not only for basic power transmission, but also for connection to weak areas of the network, where ac voltage stability could be a problem. The VSC Transmission scheme's ability to control dynamic reactive power or the ac voltage at the point of connection is particularly beneficial in such applications, but careful modelling is necessary for detailed studies. Typically, any studies performed during the feasibility and project development stage have to be refined during the implementation phase in close co-operation with the scheme supplier.

The selection of VSC Transmission as an alternative to LCC HVDC, ac transmission, or local generation, is normally motivated by financial, technical or environmental considerations. When evaluating different technologies, it is important to compare their life cycle costs. One aspect that needs special attention is the evaluation of the benefits derived from the controllability and control features available with VSC Transmission. These include:

- Real power control

- AC voltage control/Reactive power control
- Power reversal
- Damping of oscillations
- Black start
- Power Quality improvements

When comparing VSC Transmission with a comparable ac system, the net benefit of these controls should be credited to the life cycle cost of the VSC Transmission system.

8. OVERVIEW OF VSC TRANSMISSION SCHEMES IN SERVICE OR UNDER CONSTRUCTION

This section provides information about the 7 VSC Transmission systems in service or under construction at the end of 2005.

8.1 GOTLAND, SWEDEN

The purpose of the Gotland VSC Transmission scheme was to provide a 70km long transmission link for wind generation at the south of Gotland to the more populated North, from where energy can also be exported to mainland Sweden (on an existing LCC HVDC scheme), when the generation exceeds the load requirement on Gotland. Transmission of the power by underground cable was more acceptable to the population than an additional 130kVac overhead line. The VSC Transmission scheme has also resulted in power quality improvements on the island, in particular voltage flicker at the terminals of a large industrial processing plant on the East Coast has been significantly reduced. The power quality of the power from the wind generators is also significantly better than with the use of an ac overhead or cable line connection between the North and the South.

The scheme operates at ±80kVdc and has a rating of 65MVA. The VSC Transmission scheme operates in parallel with an existing 70kVac line. The scheme uses a 2-level converter with triangular carrier PWM switching at 1950Hz. Both terminals use ac voltage control, and are capable of either dc voltage control or active power control. Normally, dc voltage control is at the inverter end. The scheme operates unmanned and is controlled from the control room on Gotland.

8.2 TJÆREBORG, DENMARK

The Tjæreborg VSC Transmission scheme is a wind power transmission demonstration project, built by ELTRA, Denmark in anticipation of the construction of several large offshore wind farms. The scheme has a relatively small rating of 8 MVA, and operates at ±9kVdc with a dc cable length of only 4.5km. However, the low rating was considered sufficient for the purpose of investigating the benefits, which could be derived from the use of a VSC Transmission with a number of different wind generators.

The scheme uses a 2-level converter with triangular carrier PWM switching at 1950Hz. Both terminals use ac voltage control, and are capable of either dc voltage control or active power control. Normally, dc voltage control is at the inverter end. The interface transformers are dry type transformers. The scheme operates unmanned and is controlled from the control room at Tjæreborg Enge.

8.3 DIRECT LINK, AUSTRALIA

The Direct Link VSC Transmission scheme was built to provide a non-regulated power link for power trading between New South Wales and Queensland Australia. The use of underground cables enabled planning permission to be obtained much earlier than a competing regulated ac overhead line, thereby enabling opportunity to be taken from a significant energy price differential between the two states. The scheme consists of 3 identical parallel VSC Transmission schemes, providing a total transmission capability of 180MW, 195MVA. The ac connection points in both states are relatively weak, making the controllability of reactive power particularly useful in this application. Revenue can be earned not only when transmitting active power, but also by providing a reactive power or ac voltage control service. The use of virtually the same converter rating as for the Gotland scheme meant that the equipment could be manufactured very quickly. The three cable systems operate at ±80kVdc and have a dc cable length of 65km.

The scheme uses 2-level converters with triangular carrier PWM switching at 1950Hz. Both terminals can use ac voltage or reactive power control, and are capable of either dc voltage control or active power control. Normally, dc voltage control is at the inverter end. The scheme operates unmanned and is controlled from the grid control centre.

8.4 MURRAY LINK, AUSTRALIA

The Murray Link VSC Transmission scheme was the second non-regulated power link for power trading in Australia, and provides a link between the power networks in the states of South Australia and Victoria. As was the case for the Direct Link project, the use of underground cables enabled planning permission to be obtained relatively quickly. The scheme is rated at 200MW, ±150kVdc and the cable length is 180km, making this the longest overland cable scheme in the world. The ac network connection points at both ends of the scheme are relatively weak. As with the Direct Link scheme, revenue can be earned not only when transmitting active power, but also by providing a reactive power or ac voltage control service.

This scheme marked the second generation of VSC Transmission schemes using a transmission voltage of ±150kVdc and a 3-level NPC converters with triangular carrier PWM switching at 1350Hz. The lower PWM frequency and the use of 3-level converters resulted in a significant decrease in the power loss, compared with the earlier generation VSC Transmission schemes.

Both terminals can use ac voltage or reactive power control, and are capable of either dc voltage control or active power control. Normally, dc voltage control is at the inverter end. The scheme operates unmanned and is controlled from the grid control centre.

8.5 CROSS SOUND, USA

The Cross Sound VSC Transmission scheme provides a non-regulated energy trading link between New Haven, Connecticut and Shoreham on Long Island, Massachusetts. A 40km submarine cable across the Long Island Sound connects the two terminals. The scheme was designed and built almost at the same time as the Murray Link, and uses the same technology as that scheme, operating at ±150kVdc, but with a higher power rating of 330MW, 346MVA.

The submarine cables and fiber-optic cables were bundled together. The cable bundle was buried 6 feet below the seabed, to achieve protection against damage from fishing vessels and anchors, and to minimise the long-term impact on shellfish living on the seabed.

This scheme use second generation VSC Transmission technology with 3-level NPC converters with triangular carrier PWM switching at 1260Hz. The lower PWM frequency and the use of 3-level converters resulted in a significant decrease in the power loss, compared with the first generation VSC Transmission schemes.

Both terminals can use ac voltage or reactive power control, and are capable of either dc voltage control or active power control. Normally, dc voltage control is at the inverter end. The scheme operates unmanned and is controlled from the grid control centre.

8.6 TROLL, NORWAY

The Troll VSC Transmission scheme provides the first HVDC power connection to an offshore gas production platform. The Troll platform has 2 large compressors to enable more gas to be extracted from the sub-sea reservoirs, and to transport the gas through the pipeline to the processing station on mainland Norway. As the gas reservoir is being emptied, more and more power is needed, and it was decided to import the power from the mainland grid, rather than to provide large on-platform generators. The main reasons for the choice were financial, e.g. because of lower taxes due to reduced CO2 emissions and lower maintenance and operation costs.

Two parallel systems are being provided, each rated at 40MW and operating at ±60kVdc. The VSC Transmission substation at Kolness uses an interface transformer for the connection of the converter to the mainland 132kV ac network. The converter on the platform connects directly through the converter reactor to a high voltage motor, which is also supplied by ABB. The high voltage motor drives the pre-compressor.

This scheme uses first generation VSC Transmission technology with 2-level converters with triangular carrier PWM switching at 1950Hz. The main reason for this choice was the smaller space and lower weight occupied when compared with a 3-level NPC converter, space and weight being an extremely significant consideration for an offshore installation.

The mainland terminal is in dc voltage control and can use ac voltage or reactive power control, as required by the network operator. The offshore converter is controlled to function as a variable speed drive, capable of providing a frequency between 0 and 63Hz and an ac voltage between 0 and 56kVac. The scheme operates unmanned and is normally controlled from the onshore control centre.

8.7 ESTLINK, ESTONIA-FINLAND

The Estlink project was ordered early 2005, and will provide an interconnection between Estonia and Finland, crossing the Gulf of Finland. The primary objective of the link will be to provide the Nordic electricity market with electricity generated in the Baltic States. The European Union has approved the link as a non-regulated trading link. The rating of the interconnector is 350MW, ±150kVdc.
The VSC Transmission substation will be located at Harku, near Tallinn in Estonia and Espoo near Helsinki in Finland. The cable between the two VSC Transmission substations will include 74km submarine cables and 31km land cables. No information is yet available describing the implementation of the VSC Transmission substations.

9. FUTURE TRENDS

VSC Transmission is a relatively new technology compared with conventional LCC HVDC. Given VSC Transmission's technical advantages compared with LCC HVDC, future development of the technology is likely to lead to more widespread use of VSC Transmission.

Power losses in VSC schemes today are significantly higher than those for LCC HVDC, due to higher power losses in the converters including IGBT, filter and interface transformer losses. As indicated in Figure 9-1, the losses of the first generation of VSC-based HVDC converters were much higher than the goal value presented by the comparable LCC HVDC solution.

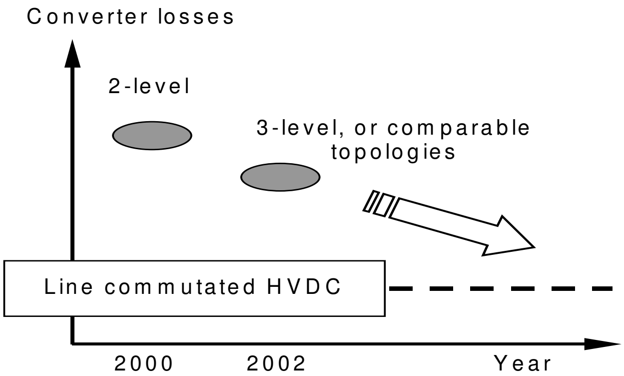

Figure 9-1: VSC Transmission power loss compared with LCC HVDC

Today the power loss of a VSC Transmission station using a 3-level converter, i.e. a converter which can switch the voltage at the ac terminal between 3 different voltage levels, is typically just below 2%, compared with about 0.8% for an LCC HVDC Station. One way to reduce power losses for a VSC Transmission scheme is to use a more advanced converter topology, but this is done at the expense of simplicity. It is also possible to reduce the power loss by the use of Optimised PWM (OPWM) switching control techniques, e.g. a 2-level converters using OPWM could have the same level of power loss as a 3-level converter with triangular PWM. It is expected that on-going semiconductor development and optimisation of the converter equipment will contribute to a further reduction in the overall power losses. However, it is unlikely that the power loss will become as low as for LCC HVDC schemes, since the conduction loss of an IGBT is considerably higher than that of a thyristor.

One trend in silicon-based IGBT development is toward higher rated voltage capability. Increasing the voltage capability will reduce the number of series-connected components required in the VSC valve, but to maintain the current capability a semiconductor with larger cross-sectional area will be required. The overall effect will likely reduce the cost of the valve. VSC Transmission requires press-pack devices, which carry a significant price premium and commercially available devices at present have a maximum rated voltage of 4.5kV, compared with 6.5kV for IGBT modules. As the market for VSC Transmission grows, the development of high-voltage press-pack devices will become more attractive, and the price differential will decrease.

VSC Transmission technology can make use of power cables that are not required to withstand voltage reversal (steady state or transient). These extruded polymeric cables may be easier to install on land and cost less than oil-impregnated cables, and may be considered more environmentally benign than overhead lines. At the end of 2005, the maximum commercially available voltage rating for extruded polymeric dc cables was 150 kVdc and was the limiting feature for the operating voltage of VSC Transmission with such cables. Further research and development aimed at increasing the voltage rating of cable technology and reducing its cost may make VSC Transmission more attractive for a number of applications.

10. CONCLUSIONS

The above has provided a very brief summary of the VSC Transmission technology. VSC Transmission has a number of technical features that are superior to those of an LCC HVDC scheme and make it especially attractive for the following applications:

- Feeding into passive networks
- Transmission to/from weak ac systems
- Land cable systems

- Supply of offshore loads
- Connection to wind farms (on-shore or off-shore) or wave power generation
- In-feeds to city centres
- Multi-terminal systems

Working Group B4.37, which concluded its work in 2004 did not identify any technical barriers to VSC Transmission becoming available at very high direct voltage and power levels. Whether such systems are developed depends upon whether or not they are competitive with LCC HVDC technology.

VSC Transmission has higher losses than LCC HVDC. This is obviously an economic disadvantage in bulk power transmission applications, since power losses are normally capitalised. However, VSC Transmission can offer system benefits in addition to those provided by an LCC HVDC scheme which may offset some or all of the disadvantage of higher power losses, e.g., ancillary services like ac voltage support or black network start.

11. RECOMMENDED FURTHER READING

VSC Transmission, Cigre Brochure 269, Working Group B4.37, April 2005.

It's Time to Connect, Technical Description of HVDC Light® technology, ABB website, www.ABB.com/hvdc.