**5.VOLTAGE SOURCED CONVERTER**

**Introduction**

A voltage-sourced converter is connected on its ac-voltage side to a three-phase electric power network via a transformer and on its dc-voltage side to capacitor equipment. The transformer has on its secondary side a first, a second, and a third phase winding, each one with a first and a second winding terminal. Resistor equipment is arranged at the transformer for limiting the current through the converter when connecting the transformer to the power network.

The resistor equipment includes a first resistor, connected to the first winding terminal of the second phase winding, and switching equipment is adapted, in an initial position, to block current through the phase windings, in a transition position to form a current path which includes at least the first and the second phase windings and, in series therewith, the first resistor, which current path, when the converter is connected to the transformer, closes through the converter and the capacitor equipment, and, in an operating position, to interconnect all the first winding terminals for forming the common neutral point.

In VSC HVDC, Pulse Width Modulation (PWM) is used for generation of the fundamental voltage. Using PWM, the magnitude and phase of the voltage can be controlled freely and almost instantaneously within certain limits. This allows independent and very fast control of active and reactive power flows. PWM VSC is therefore a close to ideal component in the transmission network. From a system point of view, it acts as a zero inertia motor or generator that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to the short circuit power, as the AC current can be controlled.

**5.1 Voltage Sourced Converter based on IGBT technology**

The modular low voltage power electronic platform is called Power Pak. It is a power electronics building block (PEBB) with three integrated Insulated Gate Bipolar Transistor (IGBT) modules. Each IGBT module consists of six switches forming three phase legs. Various configurations are possible. For example three individual three-phase bridges on one PEBB, one three phase bridge plus chopper(s) etc. The Power Pak is easily adaptable for different applications.

The IGBT modules used are one Power Pak as it is used for the SVR. It consists of one three-phase bridge (the three terminals at the right hand side), which provides the input to the DC link (one IGBT module is used for it) and one output in form of one single phase H-bridge (the two terminals to the left) acting as the booster converter. For the latter two IGBT modules are used with three paralleled phase legs per output terminal. By paralleling such PEBBs adaptation to various ratings is possible.

**5.2 GTO/IGBT (Thyristor based HVDC)**

Normal thyristors (silicon controlled rectifiers) are not fully controllable switches (a "fully controllable switch" can be turned ON and OFF at will). Thyristors can only be turned ON and cannot be turned OFF. Thyristors are switched ON by a gate signal, but even after the gate signal is de-asserted (removed), the thyristor remains in the ON-state until any turn-off condition occurs (which can be the application of a reverse voltage to the terminals, or when the current flowing through (forward current) falls below a certain threshold value known as the holding current). Thus, a thyristor behaves like a normal semiconductor diode after it is turned on or "fired".

The GTO can be turned-on by a gate signal, and can also be turned-off by a gate signal of negative polarity. Turn on is accomplished by a positive current pulse between the gate and cathode terminals. As the gate-cathode behaves like PN junction, there will be some relatively small voltage between the terminals. The turn on phenomenon in GTO is however, not as reliable as an SCR (thyristor) and small positive gate current must be maintained even after turn on to improve reliability.

Turn off is accomplished by a negative voltage pulse between the gate and cathode terminals. Some of the forward current (about one third to one fifth) is "stolen" and used to induce a cathode-gate voltage which in turn induces the forward current to fall and the GTO will switch off (transitioning to the 'blocking' state.)

GTO thyristors suffer from long switch off times, whereby after the forward current falls, there is a long tail time where residual current continues to flow until all remaining charge from the device is taken away. This restricts the maximum switching frequency to approx 1kHz.

It may however be noted that the turn off time of a comparable SCR is ten times that of a GTO. Thus switching frequency of GTO is much better than SCR.

Gate turn-off (GTO) thyristors are able to not only turn on the main current but also turn it off, provided with a gate drive circuit. Unlike conventional thyristors, they have no commutation circuit, downsizing application systems while improving efficiency. They are the most suitable for high-current, high speed switching applications, such as inverters and chopper circuits.

Bipolar devices made with SiC offer 20-50X lower switching losses as compared to conventional semiconductors. A rough estimation of the switching power losses as a function of switching frequency is shown in Figure 4. Another very significant property of SiC bipolar devices is their lower differential on-state voltage drop than similarly rated Si bipolar device, even with order of magnitude smaller carrier lifetimes in the drift region.

This property allows high voltage (>20 kV) to be far more reliable and thermally stable as compared to those made with Silicon. The switching losses and the temperature stability of bipolar power devices depends on the physics of operation of the device.

The two major categories of bipolar power devices are: (a) single injecting junction devices (for example BJT and IGBT); and (b) double Injecting junction devices (like Thyristor-based GTO/MTO/JCT/FCT and PIN diodes). In a power BJT, most of the minority carrier charge resides in the low doped collector layer, and hence its operation has been approximated as an IGBT. The limited gain of a BJT will make the following analysis less relevant for lower voltage devices.

Silicon carbide has been projected to have tremendous potential for high voltage solid-state power devices with very high voltage and current ratings because of its electrical and physical properties. The rapid development of the technology for producing high quality single crystal SiC wafers and thin films presents the opportunity to fabricate solid- state devices with power-temperature capability far greater than devices currently available. This capability is ideally suited to the applications of power conditioning in new more- electric or all-electric military and commercial vehicles.

These applications require switches and amplifiers capable of large currents with relatively low voltage drops. One of the most pervasive power devices in silicon is the Insulated Gate Bipolar Transistor (IGBT). However, these devices are limited in their operating temperature and their achievable power ratings compared to that possible with SiC. Because of the nearly ideal combination of characteristics of these devices, we propose to demonstrate the first 4H-SiC Insulated Gate Bipolar Transistor in this Phase I effort. Both n-channel and p-channel SiC IGBT devices will be investigated. The targeted current and voltage rating for the Phase I IGBT will be a >200 Volt, 200 mA device, that can operate at 350 C.

**5.3 12-pulse converters**

The basic design for practically all HVDC converters is the 12-pulse double bridge converter which is shown in Figure below. The converter consists of two 6-pulse bridge converters connected in series on the DC side. One of them is connected to the AC side by a YY-transformer, the other by a YD transformer. The AC currents from each 6-pulse converter will then be phase shifted 30°. This will reduce the harmonic content in the total current drawn from the grid, and leave only the characteristic harmonics of order 12 m±1, m=1,2,3..., or the 11th, 13th, 23th, 25th etc. harmonic. The non-characteristic harmonics will still be present, but considerably reduced.

Thus the need for filtering is substantially reduced, compared to 6-pulse converters. The 12-pulse converter is usually built up of 12 thyristor valves. Each valve consists of the necessary number of thyristors in series to withstand the required blocking voltage with sufficient margin. Normally there is only one string of thyristors in each valve, no parallel connection. Four valves are built together in series to form a quadruple valve and three quadruple valves, together with converter transformer, controls and protection equipment, constitute a converter. The converter transformers are usually three winding transformers with the windings in YYD N-connection. There can be one three-phase or three single phase transformers, according to local circumstances. In order to optimize the relationship between AC- and DC voltage the converter transformers are equipped with tap changers.



**Figure: 5.1-12pulse converter**.



**Fig: 5.2 Main elements of a HVDC converter station with one bipole consisting of two 12-pulse converter unit.**

**5.4 HVDC converter stations:**

An HVDC converter station is normally built up of one or two 12-pulse converters as described above, depending on the system being mono- or bipolar. In some cases each pole of a bipolar system consists of two converters in series to increase the voltage and power rating of the transmission. It is not common to connect converters directly in parallel in one pole. The poles are normally as independent as possible to improve the reliability of the system, and each pole is equipped with a DC reactor and DC filters. Additionally the converter station consists of some jointly used equipment.



**Fig 5.3 Mono-Polar HVDC Transmission Voltage in Station b according to reversed Polarity Convention.**

This can be the connection to the earth electrode, which normally is situated some distance away from the converter station area, AC filters and equipment for supply of the necessary reactive power.

* **Basic control principles:**

**DC transmission control:**

The current flowing in the DC transmission line shown in Figure below is determined by the DC voltage difference between station A and station B. Using the notation shown in the figure, where *rd* represents the total resistance of the line, we get for the DC current

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and the power transmitted into station B is

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In rectifier operation the firing angle α should not be decreased below a certain minimum value α min, normally 3°-5° in order to make sure that there really is a positive voltage across the valve at the firing instant. In inverter operation the extinction angle should never decrease below a certain minimum value γ min, normally 17°-19° otherwise the risk of commutation failures becomes too high. On the other hand, both α and γ should be as low as possible to keep the necessary nominal rating of the equipment to a minimum. Low values of α and γ also decrease the consumption of reactive power and the harmonic distortion in the AC networks.

To achieve this, most HVDC systems are controlled to maintain γ = γ min in normal operation. The DC voltage level is controlled by the transformer tap changer in inverter station B. The DC current is controlled by varying the DC voltage in rectifier station A, and thereby the voltage difference between A and B. Due to the small DC resistances in such a system, only a small voltage difference is required, and small variations in rectifier voltage gives large variations in current and transmitted power. The DC current through a converter cannot change the direction of flow. So the only way to change the direction of power flow through a DC transmission line is to reverse the voltage of the line. But the sign of the voltage difference has to be kept constantly positive to keep the current flowing. To keep the firing angle α as low as possible, the transformer tap changer in rectifier station A is operated to keep α on an operating value which gives only the necessary margin to α min to be able to control the current.

* **Converter current/voltage characteristics:**

The resistive voltage drop in converter and transformer, as well as the non current voltage drop in the thyristor valves are often disregarded in practical analysis, as they are normally in the magnitude of 0.5% of the normal operating voltage. The commutation voltage drop, however, has to be taken into account as this is in the magnitude of 5 to 10% of the normal operating voltage. The direct voltage *Ud* from a 6-pulse bridge converter can then be expressed by

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Where α is the firing angle,

If the converter is operating as inverter it is more convenient to operate with extinction angle γ instead of firing angle α. The extinction angle is defined as the angle between the end of commutation to the next zero crossing of the commutation voltage. Firing angle α, commutation angle μ and extinction

angle γ are related by

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In inverter mode, the direct voltage from the inverter can be written as

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The current/voltage characteristics expressed in above are shown for normal values of *id* and *dxN*. In order to create a characteristic diagram for the complete transmission, it is usual to define positive voltage in inverter operation in the opposite direction compared to rectifier operation.

It is clear that to operate both converters on a constant firing/extinction angle principle is like leaving them without control. This will not give a stable point of operation, as both characteristics have approximately the same slope. Small differences appear due to variations in transformer data and voltage drop along the line. To gain the best possible control the characteristics should cross at as close to a right angle as possible. This means that one of the characteristics should preferably be constant current. This can only be achieved by a current controller.

If the current/voltage diagram of the rectifier is combined with a constant current controller characteristic we get the steady state diagram in Figure below for converter station A. A similar diagram can be drawn for converter station B. If we apply the reversed polarity convention for the inverter and combine the diagrams for station A and station B we get the diagram in Figure below In normal operation, the rectifier will be operating in current control mode with the firing angle

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**Fig 5.4 Steady state ud/id diagram for converter station A steady state ud/id diagram for converter station A.&B**

The inverter has a slightly lower current command than the rectifier and tries to decrease the current by increasing the counter voltage, but cannot decrease γ beyond γ*min*. Thus we get the operating point A. We assume that the characteristic for station B is referred to station A , that is it is corrected for the voltage drop along the transmission line. This voltage drop is in the magnitude of 1-5 % of the rated DC voltage.

If the AC voltage at the rectifier station drops, due to some external disturbance, the voltage difference is reduced and the DC current starts to sink. The current controller in the rectifier station starts to reduce the firing angle α, but soon meets the limit α*min*, so the current cannot be upheld. When the current sinks below the current command of the inverter, the inverter control reduces the counter voltage to keep the current at the inverter current command, until a new stable operating point B is reached. If the current command at station A is decreased below that of station B, station A will see a current that is to high and start to increase the firing angle α, to reduce the voltage. Station B will see a diminishing current and try to keep it up by increasing the extinction angle γ to reduce the counter voltage. Finally station A meets the γ *min* limit and cannot reduce the voltage any further and the new operating point will be at point C.

Here the voltage has been reversed to negative while the current is still positive, that is the power flow has been reversed. Station A is operating as inverter and station B as rectifier. The difference between the current commands of the rectifier and the inverter is called the current margin. It is possible to change the power flow in the transmission simply by changing the sign of the current margin, but in practice it is desirable to do this in more controllable ways. Therefore the inverter is normally equipped with a α *min* limitation in the range of 95-105°. To avoid current fluctuations between operating points A and B at small voltage variations the corner of the inverter characteristic is often cut off. Finally, it is not desirable to operate the transmission with high currents at low voltages, and most HVDC controls are equipped with voltage dependent current command limitation.

**5.5 Master control system**

The controls described above are basic and fairly standardized and similar for all HVDC converter stations. The master control, however, is usually system specific and individually designed. Depending on the requirements of the transmission, the control can be designed for constant current or constant power transmitted, or it can be designed to help stabilizing the frequency in one of the AC networks by varying the amount of active power transmitted. The control systems are normally identical in both converter systems in a transmission, but the master control is only active in the station selected to act as the master station, which controls the current command.

The calculated current command is transmitted by a communication system to the slave converter station, where the pre-designed current margin is added if the slave is to act as rectifier, subtracted if it is to act as inverter. In order to synchronize the two converters and assure that they operate with same current command (apart from the current margin), a tele-communications channel is required. Should the telecommunications system fail for any reason, the current commands to both converters are frozen, thus allowing the transmission to stay in operation. Special fail-safe techniques are applied to ensure that the telecommunications system is fault-free. The requirements for the telecommunications system are especially high if the transmission is required to have a fast control of the transmitted power, and the time delay in processing and transmitting these signals will influence the dynamics of the total control system.