1. State of the art

Present HVDC-transmission technology was developed during a period from the end of the twenties and resulted in the first commercial transmission, Gotland, in 1954. Since then the most important achievement is the introduction of thyristor valves in the beginning of the nineteen seventies.

Of course there has been a lot of development and refinements of HVDC during the years such as lowering of losses, much more advanced control and protection, lower harmonics, lower audible sound etc, but basically it is still the same technology as in the first Gotland scheme.

The present technology has some inherent weaknesses, which to some extent limit the use of HVDC as the means to overcome these weaknesses are relatively expensive.

The most important weaknesses are the need for rotating machines in the receiving network and the risk of commutation failure, which means that for some cycles there is no transmission of power.

2. VSC Technology

HVDC was originally developed from technologies used in industrial drives systems. In order to get ideas on how HVDC could be developed it is important to follow what is happening in that area.

In industrial drives the PCC (Phase Commutated Converter) technology which is presently used in HVDC is now almost totally replaced by VSC (Voltage Source Converter) technology. The fundamental difference between these two technologies is that VSC:s needs components that can switch off the current and not only switch it on as is the case in PCC:s.

As in a VSC the current can be switched off, there is no need for a network to commutate against. This gives a possibility to control the speed of a motor in an easy way which is of course of great interest in drives applications.

In HVDC-applications it could also be of interest to use VSC Technology in order to supply “dead” networks, that is areas which lack rotating machines or does not have enough power in the rotating machines (too low short circuit power).

3. Pulse Width Modulation (PWM)

If the available switching components can only switch with low frequency, Fundamental Frequency Commutation (FFC) will probably be the right technology. In order to reduce harmonics in this case the converters have to be divided into several smaller converters operating with phase shift. Hereby 12, 24 or 48 pulse operation can be achieved and the
generation of harmonics can be reduced in proportion to the pulse number. In this case the transformers have to be relatively complicated in order to connect all these small converters.

If higher switching frequency components are available it is possible to use Pulse Width Modulation (PWM) Technology. Here only one converter is needed and the ac voltage is created by switching very fast between two fixed voltages. After low pass filtering the desired fundamental frequency voltage is created. In this case the transformer arrangement is very simple and it is not even necessary to have a transformer for the functioning of the converter. See figures 1 and 2.

With PWM it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Hereby PWM offers the possibility to control both active and reactive power independently.

This makes the Pulse Width Modulated Voltage Source Converter a close to ideal component in the transmission network. From a system point of view it acts as a motor or generator without mass 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.

Figure 1 shows one phase of a VSC converter using PWM

Figure 2 shows the PWM pattern and the fundamental frequency voltage in a Voltage Source Converter
4. IGBT

From the above it appears advantageous to shift from present Phase Commutated Converter Technology for HVDC to VSC and PWM. Why has this not happened a long time ago?

The correct answer is that there has not been semiconductor components available that have been good enough for the task.

5. The Hellsjön Project

The Hellsjön Project is the world’s first VSC HVDC transmission. The rating is 3 MW and ±10 kVdc. The converter stations are connected to separated parts of an existing 10 kV ac network. The link operates between Hellsjön and Grangesberg in central Sweden on a 10 km long temporary de-commissioned 50 kV ac line.

In this respect the IGBT is a very interesting component, as it is a MOS-device and the power need for the control of the component is very low, comparable to the power in Phase Commutated Thyristor Valves which is fed from the snubber circuits. This makes series connection possible with good voltage distribution even at switching frequencies in the kHz range.

There is a fast development of the IGBT:s and the voltage of the components has recently reached 2.5 kV and soon higher voltages are expected. The market for IGBT:s also increases very fast which add to the knowledge base of the technology itself and makes it a very interesting component for HVDC applications, so far in small scale as the rating is not yet comparable to the presently available Phase Commutated Thyristors.

Converter

The converter consists of the bridge, the converter reactor, dc capacitor, and an ac-filter.

The bridge is a six-pulse bridge, two-level, with series connected IGBT:s in each valve. Every IGBT is provided with an antiparallel diode. Valves, dc busses and dc capacitors have a low inductive design to reduce the overvoltage across the valve at turn-off. Auxiliary power to the gate drive unit is generated from the voltage across the IGBT. The semiconductors are cooled with deionized water.

Turn on/off of each single IGBT is ordered via an optical link from the control equipment on ground potential. Simultaneous firing of opposed valves will create a short circuit across the bridge.

Figure 3 shows the VSC HVDC Transmission between Hellsjön and Grangesberg
The main advantages of converters with IGBTs are:

- high impedance gate which require low energy to switch the device
- high switching frequency due to short switching times and by that low switching losses

The objective for the dc capacitor is primarily to provide a low inductive path for the turned-off current and an energy storage to be able to control the power flow. The capacitor also reduces the harmonics on the dc side.

The converter generates characteristic harmonics related to the switching frequency. The harmonic currents are blocked by the converter reactor and then the harmonic contents on the ac bus voltage is reduced by a high-pass filter. The fundamental frequency voltage across the reactor defines the power flow between the ac and dc sides.

**Control**

The converter firing control calculates a voltage time area across the converter reactor which is required to change the current through the reactor from present value to the reference value. The current order to the controller is calculated from the set power/current order or the dc voltage control. A reference voltage, equal in phase and amplitude to the fundamental frequency component of the output voltage from the bridge Ug, is calculated. The pulse pattern is generated by the pulse width modulation (PWM) where the reference voltage is compared with triangular carrier wave. If the reference voltage is higher than the carrier wave then the phase terminal is connected to the positive dc terminal and if it is lower the phase terminal is connected to the negative dc terminal.

The active power flow between the converter and the ac network is controlled by changing the phase angle (δ) between the fundamental frequency voltage generated by the converter Ug and the ac voltage on the ac bus. The power is calculated according to formula assuming a lossless reactor.

\[ P = \frac{U_g \cdot U_n \cdot \sin \delta}{XL} \]

The reactive power flow is determined by the amplitude of \( U_g \) according to formula. The amplitude is controlled by the width of the pulses from the converter bridge Ug.

\[ Q = \frac{U_g \cdot (U_g - U_n \cdot \cos \delta)}{XL} \]

The maximum fundamental voltage out from the converter depends on the dc voltage.

**Operation**

The converter station can be remotely controlled and monitored from any of the two stations or another remote location through a dial up telephone line.

When the transmission should start up, both stations can be energized separately. The ac breakers are closed which means that the dc busses are energized through the antiparallel diodes in the bridge. When the gate drive units are charged the converters in the two stations can be connected by the switches on the dc side. The first converter which is deblocked will control the dc voltage then the other converter is

Figure 4 shows the main equipment of a typical transmission
deblocked and the transmission of active power can start.

Normal operation modes mean that each station controls its reactive power flow independent of the other station. However, the active power flow into the dc network must be balanced which means that active power out from the network must equal the active power into the network minus the losses in the system. Any difference means that the other station can set any active power order within the limits for the system. The voltage controlling station will now adjust its power order to ensure power balance, meaning constant dc voltage. This will be achieved without telecommunication between the stations just based on measurement of the dc voltage.

Disturbances in the system
If a converter, with prefault power from the dc network to ac network, is blocked at high load, the energy stored in inductances in the circuit will charge the dc capacitors and the dc voltage will increase. The dc voltage controlling station will counteract by decreasing and even reverse the active power flow into the dc system to maintain the dc voltage. The converter in operation can continue to operate and act as SVC and control the required reactive power flow.

At opposite prefault active power flow the dc voltage will drop at a converter outage. The remaining converter will now control the dc voltage and restore the dc voltage and at the same time control the required reactive power flow.

At an ac system ground fault the current control will rapidly lower the fundamental frequency voltage out from the bridge to reduce the current down to prefault value.

Factory system test
Each of the converters was commissioned separately and operated as SVC, consuming and generating reactive power. In this mode all control and monitoring functions were verified before the two converters were connected together to an HVDC transmission. The complete system was then connected in a round power mode and tested at high active power load before the delivery to site. Both converters were connected to the same 10 kV ac feeder. The active power was flowing between the converters and the ac feeder had to provide the difference in reactive power to the converters and the losses in the circuit.

Site operation
The transmission has been in trial operation since mid March 1997 and an extensive test program is performed. The operation experience has been entirely positive. The transmission is very stable and performs as predicted, both during steady-state and transient conditions. The measurements have indicated that the converters will be able to fulfil applicable requirements on sound power level, harmonic distortions, telephone disturbances and electromagnetic fields.

6. Characteristics for VSC HVDC Transmission
With the main characteristics shown above the VSC Converter based transmissions will be feasible for a variety of applications for which conventional HVDC is unable to compete today, either from economical or from technical point of view.

The VSC convertor has a simple and straightforward circuit solution. This provides for a compact and robust mechanical design, by which the convertor equipment is placed in simple module type housings, see Figure below. A VSC convertor station with ratings up to 20 MW and below ±30 kV will occupy an area less than approximately 250 square meters.

The modular design will give opportunity to preinstall the equipment at factory and run highly complete tests before shipment.

The technical simplifications such as small filters, no or simplified transformers, less switching equipment and simple civil works contribute to small footprint and easy handling.
The plant production process will be based on a set of standardized sizes with module drawings ready on the shelf. The need for engineering will thereby be limited and for a normal project basically all equipment will be defined already from start.

The simple circuit solution makes it possible to design a station, that does not need stops for regular scheduled maintenance. The scheduled maintenance could be limited to checking of movable equipment such as pumps and fans for cooling, resins for cooling water quality and batteries. Automonitoring of status so that faults will be automatically detected and alerted will give the possibility to rapidly exchange faulty equipment.

7. Applications

The Hellsjön test installation is rated 3 MW, ±10 kV dc corresponding to a direct current of 150 A. This gives the base for what practical sizes could be installed in the near future, pointing to a power range up to and around 50 MW in which VSC HVDC convertors can today be expected to appear. Applications can be referred to distant loads or distant generation but also connection of small loads between asynchronous networks back-to-back will now be economic.

- Small isolated remote loads

Many isolated communities are not connected to the electrical grid and are dependant on expensive local generation for their needs. The VSC transmission concept for dc makes it feasible, in many cases, to connect these communities to the main grid where cheap electricity is available. By doing so the cost for electricity can be reduced at the same time as the environmental concept of the supply is improved. With the use of modern extruded dc cables underground transmission would be in the same order of cost as overhead line transmissions.

The receiving network can be passive, i.e. the output from the VSC converter is an ac voltage which can be controlled to both magnitude and frequency.

- Power supply to islands

The power supply to small islands is often provided by expensive local diesel generation. By installing a VSC transmission and a low cost extruded cable, cheap electricity from the main-land grid can be imported and the local diesel generator can be shut off.

- Infeed to cities

Adding new transmission capacity by ac lines into city centres is costly and in many cases the permits for new ROW are difficult get. A dc cable needs less space than an ac overhead line and can carry more power than an ac cable and is therefore many times the only practical solution, should the city centre need more power.

- Remote small scale generation

Remote small scale generating facilities such as low-head hydropower and wind power have normally not been economic to develop, due to
too high transmission costs and low transmission capacity of the ac lines.

A VSC transmission link will bring capacity up and transmission cost down. Remote small scale generating capacity will be feasible to develop and connect to the main grid or to remote loads and by that maximise the use of renewable energy resources.

- Off-shore generation

Oil-platforms are today burning excess gas instead of generating electric power and transmitting it to the mainland network. The reason for this is that the available transmission systems have not been proved economic. The VSC converter combined with extruded HVDC cables is a feasible alternative and thus useless burning of gas can be avoided.

- Multiterminal

The output from a VSC converter always has the same polarity. This makes it easy to use as a building block in a multi-terminal system. To a dc-bus with fixed polarity any number of VSC converters can be connected, and by that a meshed dc-system with the same topology as an ac system can be built.

- Tappings

A tapping is a special case of a multiterminal system and will automatically fit into a VSC transmission system. Another interesting solution is the use of the shield wire of a large bi-polar HVDC transmission for a separate VSC transmission as an alternative to a tapping on the main land.

8. Conclusions

The development of power semiconductors, specifically IGBT’s has led to that small power HVDC transmissions based on VSC convertors will now be available and economical for a variety of applications.

In addition such installations have several technical characteristics that make them very attractive.

- possibility to connect to passive load
- separate control of active and reactive power
- no contribution to short circuit currents
- no need of fast communication
- small and compact