HVDC Light – DC transmission based on voltage sourced converters

In the past, high-voltage DC links have been used almost exclusively to transmit very high powers over long distances. HVDC Light is a new transmission technology based on voltage sourced converters and insulated gate bipolar transistors that extends the economical power range of HVDC transmission down to just a few megawatts. Besides being a cost-competitive alternative to conventional AC transmission and local generation, for example in remote regions and on small islands, it also opens up new possibilities for improving the quality of supply in AC power networks.

Development of the high-voltage direct current (HVDC) transmission technology in use today began in the late 1920s, going commercial in 1954 with the world's first HVDC transmission link between the island of Gotland and the mainland of Sweden. The most important innovation in the meantime has been the thyristor valve, which was introduced at the beginning of the 1970s.

Although extensive development work has greatly refined HVDC transmission over the years and led to lower losses, more advanced control and protection, reduced harmonics and lower audible sound, etc, the technology has remained basically unchanged since the first Gotland link.

Also, the present technology has some inherent weaknesses that are relatively expensive to overcome and to some extent limit the use of HVDC. The predominant weakness is the need for rotating machines in the receiving network and the attendant risk of commutation failure, during which no power is transmitted for several cycles.

Voltage sourced converter technology

HVDC was originally developed from technologies used in industrial drive systems. To determine the direction in which further development of HVDC could go, it is therefore useful to look at what is happening in that sector.

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Phase-Commutated Converter (PCC) technology, which is the technology currently in use in HVDC transmission, has now been almost totally replaced in industrial drives by Voltage Sourced Converter (VSC) technology. The fundamental difference between these two technologies is that VSCs need components that can also switch off the current, and not only switch it on as in the case of PCCs.

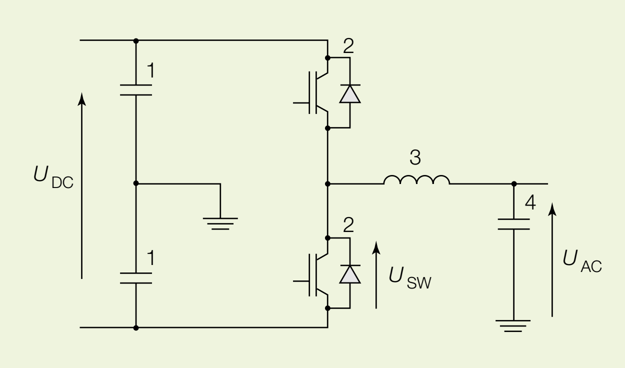
Since the current in a VSC can be switched off, there is no need for an active commutation voltage from the connected network. This makes it easier to control the speed of a motor, which of course is of great interest for drive applications.

A possible use of VSC technology in HVDC applications could be to supply 'dead' networks, ie sections in which there are no rotating machines or in which the short-circuit powers of the rotating machines are very low.

Pulse-width modulation

If the available switching components are only capable of low-frequency switching, Fundamental Frequency Commutation (FFC) is likely to be the preferred technology. To reduce the harmonics, the converters have to be divided into several smaller converters operating with phase shift. 12, 24 or 48 pulse operation can be achieved in this way, and the generation of harmonics can be reduced in proportion to the pulse number. In such cases, relatively complicated transformers are needed for the connection of the converters.

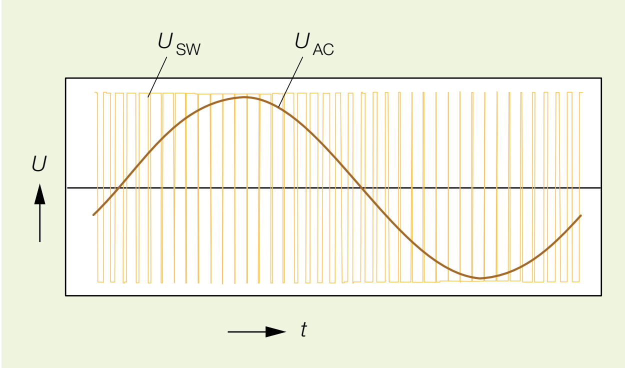
When components capable of higher switching frequencies are available, Pulse Width Modulation (PWM) technology is an option. Only one converter is needed in this case, the AC voltage being produced by switching very rapidly between two fixed voltages. To obtain the desired fundamental frequency voltage, lowpass filtering is necessary. The transformer ar-



One phase of a voltage sourced converter (VSC) using pulse width modulation (PWM) **1**

U_{AC} AC voltage
U_{DC} DC voltage
U_{SW} Converter PWM voltage

1 *DC capacitor*
2 *IGBT valve*
3 *Converter reactor*
4 *Filter*



Pulse width modulation (PWM) pattern and the fundamental frequency voltage in a voltage sourced converter **2**

t Time
U Voltage

U_{AC} AC voltage
U_{SW} Converter PWM voltage

rangement is very simple with this technology and it is not even necessary to install a transformer for the converter **1**, **2**.

With pulse width modulation any phase angle or amplitude is possible – within certain limits – by changing the PWM pattern, which can be done almost instantaneously. As PWM allows independent control of both the active and reactive power, the PWM voltage sourced converter comes close to being the almost ideal transmission network component. From the system's point of view, it acts as a motor or generator without mass and is able to control active and reactive power almost instantaneously. Also, since the AC current is controllable the converter does not contribute to the short-circuit power.

Insulated gate bipolar transistor

Considering the significance of the advantages discussed above, it may be asked why the shift from PCC technology to VSC and PWM did not take place a long time ago. The reason is that, until now, none of the commercially available semiconductor components have been good enough for the job.

One component with interesting possibilities for HVDC applications is the Insulated Gate Bipolar Transistor (IGBT). Being a Metal Oxide Semiconductor (MOS) device, it needs only a very low power for its control (comparable with the power used to control phase commutated thyristor valves, which can be supplied by the snubber circuits). This makes series connection possible, with good voltage distribution even at switching frequencies in the kHz range.

Development of the IGBT has progressed very fast and its voltage rating has now reached 2.5 kV, with higher voltages expected soon. The market for IGBTs is also growing quickly, which adds to the knowledge base for this technology. Use of the IGBT in HVDC applications has so far only been on a small scale as the rating is not yet comparable with that of the phase-commutated thyristors presently available.

The Hellsjön project

The Hellsjön project is the world's first VSC-based HVDC transmission system **3**. The converter stations of this test installation, which is rated at 3 MW and ±10 kV DC, are connected to separated parts of an existing 10-kV AC network. The link operates between Hellsjön and Grängesberg in central Sweden on a 10 km-long, temporarily decommissioned 50-kV AC line **4**.

Converter

The converter in each station consists of the bridge, converter reactor, DC capacitor, and AC filter **5**.

The bridge is a six-pulse type, on two levels, with series-connected IGBTs in each valve. Each IGBT is provided with an antiparallel diode. The valves, DC buses and DC capacitors feature a low inductive design, which reduces the overvoltage across the valve at turn-off. Auxiliary power for the gate drive unit is obtained from the voltage across the IGBT. The semiconductors are cooled with deionized water.

Hellsjön test installation in Sweden. The world's first HVDC Light transmission link is rated at 3 MW ±10 kV and uses a 10 km-long, temporarily decommissioned AC line. **3**

1 *AC filter*
2 *Converter reactors*
3 *Valves and DC equipment*
4 *Control equipment*
5 *Cooling system*

The turn-on/off command for each individual IGBT is sent from the control equipment (at earth potential) via an optical link.

The main advantages of an IGBT-based converter are its:

- High impedance gate; only low energy is needed to switch the device.
- High switching frequency, resulting in low switching losses.

The primary task of the DC capacitor is to provide a low inductive path for the turned-off current and energy storage capability to allow control of the power flow. The capacitor also reduces the harmonics on the DC side.

The converter generates characteristic harmonics on the basis of the switching frequency. Harmonic currents are blocked by the converter reactor and the harmonic content of the AC bus voltage is reduced by a highpass filter. The fundamental frequency voltage across the converter reactor defines the power flow between the AC and DC sides.

Control

The converter firing controller calculates the voltage-time area across the converter reactor required to change the current flowing through the reactor from its present value to the reference value. The current command to the controller is calculated from the set power/current command or from input signals received from the DC voltage control. A reference voltage is calculated which is equal in phase and amplitude to the fundamental frequency component of the bridge output voltage U_g. The pulse pattern is generated by the PWM.

The reference voltage is compared with a triangular carrier wave. If the reference voltage is higher than the carrier wave the phase terminal is connected to the positive DC terminal, if it is lower the phase terminal is connected to the negative DC terminal.

The active power P flowing between the converter and the AC network is controlled by changing the phase angle δ between the fundamental frequency voltage generated by the converter, U_g, and the AC bus voltage, U_n. Assuming a no-loss reactor, P is calculated according to the formula:

$$P = \frac{U_g \cdot U_n \cdot \sin\delta}{X_1}$$

X_1 Reactance of converter reactor

The reactive power flow Q is determined by the amplitude of U_g in accordance with the formula below. The amplitude is controlled by the pulse width of the output voltage of the converter bridge.

$$Q = \frac{U_g \cdot (U_g - U_n \cdot \cos\delta)}{X_1}$$

The maximum fundamental voltage generated by the converter depends on the DC voltage.

Operation

The converter station can be remotely controlled and monitored from either of the two stations or from any other remote location over a telephone line.

When starting up transmission, both stations can be energized separately. Since the AC breakers are closed, the DC buses 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 via the switches on the DC side. The first converter to be deblocked controls the DC voltage, whereupon the other converter is deblocked and the transmission of active power can start.

In the normal operating modes each station controls its reactive power flow independently of the other. However, the active power flow into the DC network must be balanced, which means that the active power leaving the network must equal the active power received by the network, minus the losses in the system.

Any difference will cause the DC voltage in the system to rapidly increase or decrease. To achieve this power balance one of the stations controls the DC voltage. This means that the other station can set any active power within the limits given for the system, and the station controlling the voltage will adjust its power signal to ensure the balance (ie constant DC voltage). Balance is achieved without communication between the stations, being based simply on measurement of the DC voltage.

Disturbances in the system

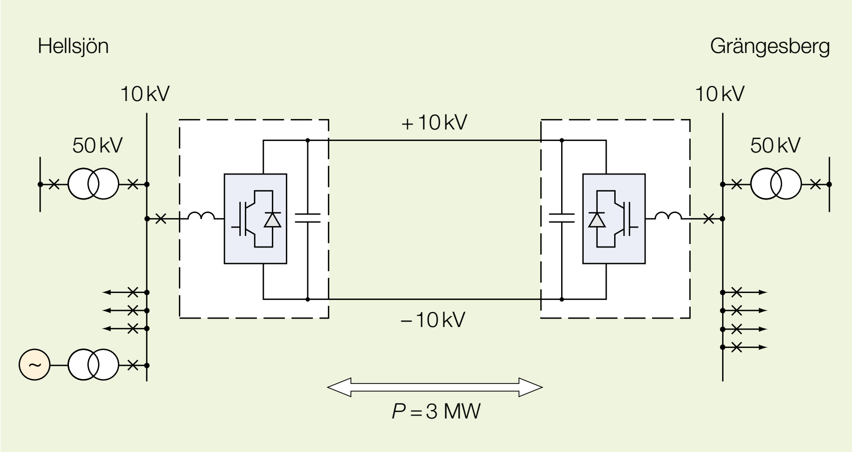
If a converter is blocked at high load when pre-fault power flows from the DC network to an AC network, the energy stored in the inductances in the circuit will charge the DC capacitors and the DC voltage will increase. The station that controls the DC voltage will counteract by lowering or even reversing the active power flow into the DC system in order to maintain the DC voltage level. The converter in operation can continue to act as a Static Var Compensator (SVC) and control the required reactive power flow.

With pre-fault active power flow in the opposite direction, the DC voltage drops in the event of a converter outage. The converter still operating will now control and restore the DC voltage, and at the same time control the required reactive power flow.

In the event of an earth fault in the AC system the current controller rapidly lowers the fundamental frequency voltage generated by the bridge to reduce the current to its pre-fault value.

System testing in the factory

Each of the converters was commissioned separately and then operated as an SVC, consuming and generating reactive power. All the control and monitoring functions were verified in this way. Afterwards, the two converters were connected together on the DC side to form a DC transmission link fed from the same 10-kV AC terminal and tested at high active power load before delivery to the site. Active power flowed from the AC network to the DC side via one converter and back to the AC side via the othe converter. The AC network then only had to make up the difference in power (ie, the losses in the circuit).



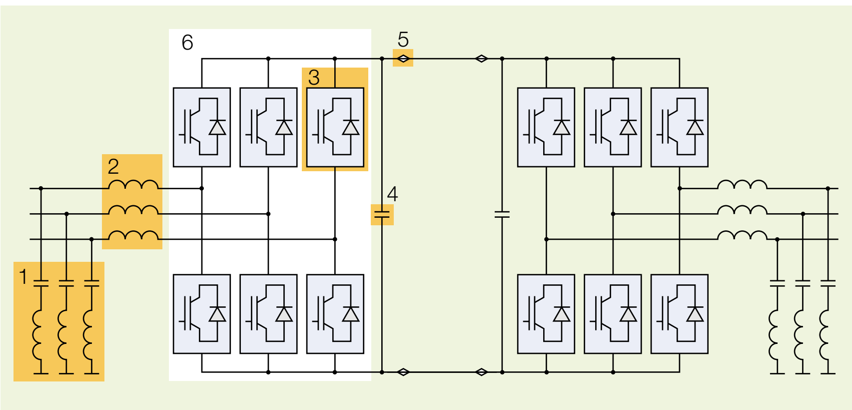
The VSC HVDC transmission link between Hellsjön and Grängesberg. Power P can flow in either direction, as indicated by the arrows. There is no generator in the Grängesberg station, which is connected to the main grid. **4**

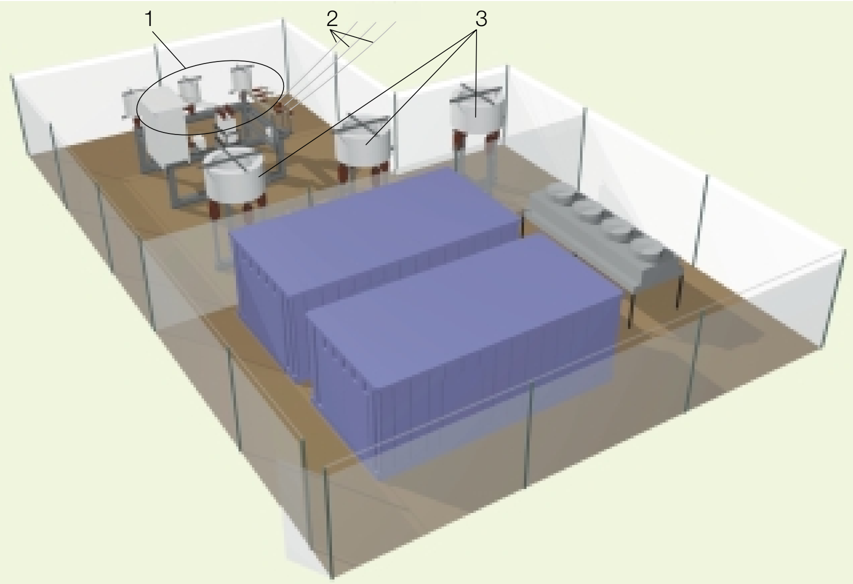
Site operation

The transmission link has been in trial operation since mid-March 1997 and an extensive test programme has been carried out. Operational 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 the requirements regarding sound level, harmonic distortions, telephone disturbances and electromagnetic fields.

Main equipment of a typical HVDC transmission link **5**

1 *Filter*
2 *Converter reactor*
3 *Converter valve*
4 *Commutation capacitor*
5 *Connection to cable*
6 *Converter*





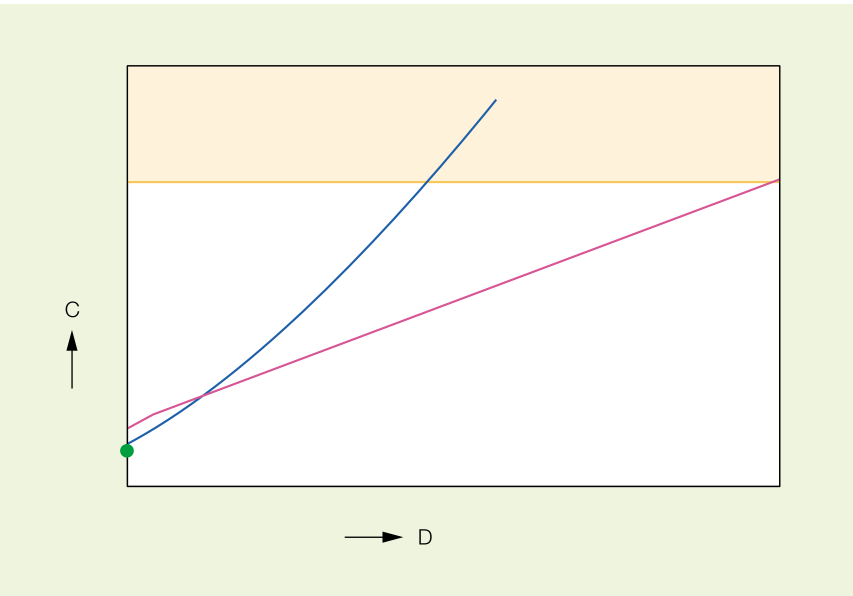
Model of a typical layout of a 20-MW converter station **6**

1 *AC filter*
2 *AC connection*
3 *Converter reactors*

Comparison of typical costs for AC and DC transmission and local diesel generation (basis: 20 MW) **7**

C *Cost per kWh*
D *Distance from AC grid*

Beige *Local diesel generation*
Blue *AC plus overhead line*
Red *HVDC Light with cable*
Green *Energy cost for AC grid*



Characteristics of VSC HVDC transmission

VSC-based transmission links are well suited for a variety of applications for which conventional HVDC is unable to compete today from the economical or technical standpoint.

The simplicity of the VSC circuit allows a compact and robust mechanical design, with the converter equipment housed in simple, modular structures **6**. A VSC-based converter station with a rating of up to 20 MW at less than ±30 kV will occupy an area of less than 250 square metres.

Due to its modular design, the equipment can be installed and wired already in the factory and thoroughly pre-tested before shipment. Technical simplifications, such as small filters, no (or simplified) transformers, reduced switchgear and considerably less complex civil works, contribute to a small footprint and easy handling.

The plant production process will be based on a set of standardized sizes and off-the-shelf drawings, which will limit the engineering work that is needed. Practically all the equipment for a normal project can be defined already at the start.

The simple circuit also enables a station to be designed which does not need to be shut down for regular maintenance. Routine maintenance can be limited to the inspection of equipment such as pumps, fans, resin bottles and batteries. Integrated diagnostics systems automatically detect and signal faults, allowing the rapid identification and replacement of faulty equipment.

Applications

Experience with the Hellsjön test installation has provided important information and gives a good idea of the ratings that could be installed in the near future. At the present time it points to a power range of up to about 50 MW for VSC-based HVDC systems. Possible applications include supplying power to distant loads and the connection of distant generating plants, while the back-to-back connection of small loads located between asynchronous networks will now also be economically viable.

Small, isolated remote loads

Isolated communities are often not connected to the electrical grid, being dependent on expensive local generation instead. The VSC HVDC concept will make it feasible for many of these communities to be connected to the main grid, and so gain access to cheap, clean electricity. Another environmental 'plus' is that buried extruded DC cables can be used. The Hellsjön project has shown that the cost of underground transmission with these cables would be of the same order of magnitude as that of overhead lines **7**. What is more, the receiving network can be passive, with the VSC producing AC voltage that can be controlled in terms of both its magnitude and frequency.

Power supply to islands

Small islands often have to rely on expensive local diesel generation plants for their power supply. By installing a VSC transmission link and low-cost extruded cable, cheap electricity can be imported from the mainland grid and the local diesel generator can be shut down.

City center infeeds

Adding new transmission capacity by routing AC lines into city centers is costly, and permits for new rights of way are increasingly difficult to obtain. A DC cable not only takes up less space than an overhead AC line but also can carry more power than an AC cable and is often the only practical solution for city centers needing more power.

Remote small-scale generation

Remote, small-scale generating facilities, such as low-head hydropower plants and wind power stations, have not normally been economically viable in the past because of the excessively high operating costs and low transmission capacity of the AC lines.

A VSC transmission link will increase capacity and cut transmission costs. Small-scale generating plant in remote locations can be connected to the main grid or to remote loads, thereby optimizing the way in which renewable energy resources are used.

Off-shore generation

Off-shore oil platforms today burn off excess gas instead of using it to generate electricity which can be transmitted to the mainland network. The reason for this is that the available transmission systems have not proved economical enough. The VSC solution, combined with extruded HVDC cables, is a viable alternative and would avoid the wasteful burning of a valuable resource.

Multi-terminal systems

The output from a voltage sourced converter always has the same polarity, making it easy to integrate in a multi-terminal system. Any number of VSCs can be connected to a DC bus with fixed polarity to form a meshed DC system with the same topology as an AC system.

Tappings

Tappings, which represent a special case in multi-terminal systems, automatically fit into VSC transmission schemes. As an alternative to having a tap on the mainland, the shield wire of a large bipolar HVDC transmission system could be used for a separate VSC transmission link.

Summary

Continuing development of power semiconductors, in particular of IGBTs, has led to HVDC Light. This low-power VSC-based HVDC transmission system is economically viable for a variety of applications.

HVDC Light further promises power quality improvements, as it eliminates the problem of voltage drops on long AC distribution lines. In combination with new control algorithms, it also offers new levels of performance regarding flicker reduction.

Other benefits which make VSC-based HVDC transmission very attractive are:

- Passive AC loads can be supplied from a DC source.
- Active and reactive power can be controlled separately.
- VSCs do not contribute to the short-circuit power.
- No need for fast communication between stations.
- Small size and compact layout.

By combining all these advantages, HVDC Light has positioned itself as a very interesting alternative to local generation or conventional AC transmission.

Reference

[1] G. Asplund, K. Eriksson, K. Svensson: DC transmission based on voltage sourced converters. CIGRE SC14 Colloquium, South Africa, 1997.

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