SUMMARY
Voltage Source Converters (VSC) have for the first time been used for HVDC transmission in a real network. Experience from the design and commissioning of the transmission shows that the technology has now reached the stage where it is possible to build high voltage converters utilising Insulated Gate Bipolar Transistors (IGBTs). Operation and system tests have proved that the properties that have been discussed for many years regarding VSCs for HVDC are a reality now. They include independent control of active and reactive power, operation against isolated a.c. networks with no generation of their own, very limited need of filters and no need of transformers for the conversion process.

This is only the first installation of VSC for HVDC. The development of semiconductors and control equipment is presently very rapid and it is evident that this technology will play an important role in the future expansion of electric transmission and distribution systems.

1. INTRODUCTION
On March 10, 1997 power was transmitted on the world’s first HVDC transmission with VSC converters between Hellsjön (Hn) and Grängesberg (Gbrg) in central Sweden. Since then extensive testing has been performed in order to prove that the Voltage Source HVDC technology fulfils the expectations that since long time have been expressed in different publications.

This article describes the technology that has been utilised, the development of the project and the tests that have been performed during operation.

So far the experience of tests and operation is most encouraging and the VSC seems to be very suitable for small scale HVDC as it can operate at any short circuit ratio, even against isolated a.c. networks with no other generators in the system. They can also connect isolated generators to the grid or to isolated loads.

2. VSC TECHNOLOGY AND PULSE WIDTH MODULATION (PWM)
HVDC was originally developed from technologies used in industrial drive systems. There the PCC (Phase Commutated Converter) technology which is at present being used for HVDC has now almost entirely been replaced by VSC technology. The fundamental difference between these two technologies is that VSCs need components that can turn-off the current and not only turn it on as is the case with PCCs.

Since in a VSC the current can be turned off, there is no need for a network to commutate against. In HVDC-applications it could then be advantageous to use the VSC technology especially to supply passive load networks, that is areas which lack rotating machines or which do not have enough power in the rotating machines (short circuit power too low).

With the appearance of high switching frequency components, such as IGBTs it becomes advantageous to use Pulse Width Modulation (PWM) Technology. In a VSC converter the a.c. voltage is created by switching very fast between two fixed voltages. The
desired fundamental frequency voltage is created through low pass filtering of the high frequency pulse modulated voltage. See Figs. 1 and 2.

3. THE HELL’SJÖN PROJECT, A DEMONSTRATION FACILITY

Development work on VSC converters has been going on for a long time within ABB. During this development it was realised that the IGBT should be a very interesting component, as it is a MOS-device and the power requirement for the control of the component is very low. By this series connection of many semiconductors with good voltage distribution even at switching frequencies in the kHz range should be possible.

3.1 Co-operation with the local utility

In 1994 the development on VSC converters was concentrated into a project to put two VSC converters for small-scale HVDC based on IGBTs into operation. Through co-operation with the local utility, VB-Elnät, it became possible to design the transmission for operation in a commercial network. An existing 10 km long 50 kV back-up a.c. line between Hellsjön and Grängesberg in central Sweden was made available for the project. VB-Elnät also provided space in the stations and connections to the a.c. networks. The transmission rating was determined to 3 MW, somewhat above the hydro generator rating at Hellsjön and with a direct voltage of ±10 kV d.c. The converter stations are connected to separate parts of an existing 10 kV a.c. network.

3.2 Simulation and testing

During the development of the project the various characteristics and behaviours of VSC converters, PWM control, IGBT valves etc. were tested in digital and analogue simulations. Finally, the complete transmission stations were connected in a round power circuit at a laboratory in Ludvika. By the end of 1996, and after a comprehensive synthetic testing, the equipment was moved to the field for installation and testing. On March 10, 1997 power was transmitted between Hellsjön and Grängesberg in the Hellsjön Project, the world’s first VSC HVDC transmission.

3.3 Converter design

Main circuits

The converter consists of the bridge, the converter control, the converter reactor, d.c. capacitor, and an a.c. filter.

The bridge is a six-pulse bridge, two-level, with series connected IGBTs in each valve. Every IGBT is provided with an antiparallel diode. Auxiliary power to the gate drive unit is generated from the voltage across the IGBT. Turn on/off of each individual IGBT is ordered via an optical link from the control equipment on ground potential. The semiconductors are cooled with deionized water.

The objective for the d.c. capacitor is primarily to provide a low inductive path for the turn-off current, and an energy storage to be able to control the power flow. The capacitor also reduces the harmonics on the d.c. side.
The converter generates characteristic harmonics related to the switching frequency. The ac currents are smoothed by the converter reactor and then the remaining harmonic contents in the ac bus voltage are reduced by a high-pass filter.

Depending on the system requirements the converter may be equipped with two more components:

- Overvoltage limiter (chopper) for fast discharge of the d.c. capacitor if the d.c. voltage exceeds the maximum d.c. bus voltage for a deblocked converter. This function is realised by a fast switch and a resistor.
- DC line switches, if fast isolation of the converter is required at d.c. line faults.

In this project both switches specified above are IGBT valves similar to the valves in the bridge.

The main circuit components are as shown in Fig. 3.

![Main circuit components](image)

Fig. 3 Main circuit components

**Control**

The fundamental frequency voltage across the reactor defines the power flow between the a.c. and d.c. sides. The converter firing control calculates a voltage time area across the converter reactor which is required to change the current through the reactor from actual value to the reference value. The active power flow between the converter and the a.c. network is controlled by changing the phase angle between the fundamental frequency voltage generated by the converter (Ug) and the a.c. voltage on the a.c. bus. The reactive power flow is determined by the amplitude of Ug which is controlled by the width of the pulses from the converter bridge.

The current order to the controller is calculated from the set power/current order or the d.c. 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 the triangular carrier wave.

**4. DEVELOPMENT TESTS**

**4.1 Control equipment**

The control system performance has been extensively tested in an analogue simulator. The main circuits in this low power simulator is represented by physical models with properties corresponding to full-scale components. The main advantage of the simulator is that control equipment identical to the full-scale system is used. The dynamic performance of the system has been studied during different types of disturbances in the system, such as faults in the a.c. system, d.c. faults and converter faults.

Similar development of the control system has also been performed by digital simulation in the program EMTDC. The control equipment for the converter, main circuits and a.c. system have been represented in detail.

To further ensure correct operation of the system a medium voltage test circuit was set up. The test circuit included two converters with a.c. reactors and filters and a representation of a d.c. overhead line. Each valve in the bridge was represented by one industrial IGBT. The control equipment was the actual equipment later delivered to site. In this test circuit normal operation of a HVDC transmission with VSC converters was verified. Steady state modes such as d.c. voltage control, active and reactive current control and also some fault conditions were checked.

**4.2 VSC valve**

The most important task to solve was how to achieve an even voltage distribution between a large number of series connected IGBTs in a valve function. To accomplish this a special Gate Unit (GU) was designed which, together with a voltage divider across each IGBT, maintains a proper voltage division within the valve during both blocking and switching conditions.

The GU and the voltage divider was developed by intensive testing of a stack of IGBTs switching in a single-pulse test circuit. The single-pulse test circuit consisted of one converter phase leg, one d.c. capacitor and a reactor of suitable size. The detailed behaviour of the switching transients was studied at IGBT turn-on, IGBT turn-off and diode turn-off. Proper gate control combined with a small voltage divider made it possible to achieve both good voltage division and low switching losses.
4.3 Factory system test
Before delivery to site the complete system was tested with full rated voltage (10 kV a.c. and ± 10 kV d.c.) and current. Each converter was first tested as a single unit operating as SVC. Then the two converters were connected and operated in round power mode as per Fig 4.

The ac terminals were connected together which means that the active power only circulates between the converters, and the a.c. feeder only feeds the active power corresponding to the losses in the system. The reactive power could be altered in each converter independent of each other within the limit for the power flow in the feeder. This configuration allows full-scale test operation with a relatively weak feeder.

Extensive tests were performed primarily to verify the steady state operation of the converter bridge and to check important performance of a valve with several series connected IGBTs.

5. COMMISSIONING
Thanks to the factory testing of the complete system the commissioning at site was very fast. The two stations were commissioned one by one, operating as SVC, consuming and generating reactive power. This means that each station could be properly tested as a single unit independent of the other station. After that the two stations were connected to the d.c. overhead line and the flow of active power could start.

5.1 Steady-state operation and converter trip.
Steady state operation was verified which means d.c. voltage control in one station and current control in the other. The dynamic performance at typical protective actions was demonstrated. These cases are;

- trip of the d.c. voltage controlling station with the power flow out from the d.c. system.

In the first case the d.c. voltage will drop transiently and then the remaining station will take over the d.c. voltage control and continue to operate and control both the reactive power order and the d.c. voltage (transiently to a lower level).

![Fig. 4. Factory system test](image)

![Fig. 5. Trip of the voltage controlling station](image)
5.2 Power system compatibility
Commissioning also included measurements of the following properties of the converters.
- Sound power level
- Radio interference
- Harmonic distortion

All three items are mainly related to the turn-on and turn-off of the valves.

Sound Power Level
The dominating sound generated in the converter station is related to the switching frequency. The different sources of sound within the converter station have been identified and the total sound level at different directions and distances has been measured. The sound level from the converter station did not exceed 40 dB(A) at a distance of 40 m from the station fence which was the target for the design.

Radio Interference (RI)
RI measurements have been performed at Hellsjön and Grängesberg.

The most appropriate standard defining the limits in this case is ENV 50121-5 (Railway application- Electromagnetic compatibility, Part 5: Fixed power supply installations). The railway standard requires a measurement at a distance of 3 m from the fence surrounding the installation.

The measurements are performed at a distance of about 30 m from the radiating source in order to avoid electrical shielding from the surrounding fence of the HVDC station. The signal level at that distance from the fence has then been rescaled back to 3 m.

The measured RI meet the required levels given in ENV 50121-5 for the frequency range 9 kHz to 1 GHz.

Harmonic Distortion
The a.c. filter arrangements consist of a single branch high-pass filter on the a.c. side. The bank size is 10 % of rated converter power and the filter is tuned to the 40th harmonic, (q=10).

The harmonic distortion level (THD) on the a.c. side at Hellsjön have been measured at various load conditions of the converter. The average level of the measured total harmonic distortion up to 3 kHz was 3.8 %. This value can be compared with target levels of 5.0 % (IEEE Std 519-1992) or 8.0 % (Electra 149, Aug. ’93 page 75 table I) for bus voltages below 69 and 45 kV respectively. The nominal a.c. bus voltage is 10.5 kV.

The measured distortion corresponds to a THD of 2%.

6. SYSTEM TESTS

6.1 Radial interconnection of synchronous generator and converter.
The aim of the test is to prove the feasibility of feeding a VSC converter from an isolated synchronous generator. The operation mode is constant power control and a.c. voltage control at the synchronous generator and frequency control at the converter.

6.1.1 Main circuit
The main circuit configuration at Hellsjön was as shown in Fig. 7.

Fig. 7. Isolated operation with the generator

All a.c. lines were disconnected from the 10 kV bus.
6.1.2 Frequency control design.

The exciter voltage control at the generator and the current control of the VSC are disregarded in the model analysis due to their fast dynamic behaviour with respect to the machine time constants.

Included in the analysis is the machine inertia, the frequency calculation and the measurement filters.

The control-law is mainly based on Equation 6-1 and the measurement filter functions. The control is based on a PI-regulator.

Equation 6-1

\[
\frac{d^2 \delta}{dt^2} = -\frac{\omega_n}{2H} (P_m - P)
\]

\[
\omega_n = 2\pi f
\]

\[
H = 3.3 \text{ [s]}
\]

Where:

- \( S_n \) = Rated Machine Power
- \( P_m \) = Mechanical Power
- \( P \) = Electric Power
- \( f \) = Nominal Frequency
- \( \delta \) = Angular Position
- \( H \) = Per-Unit Inertia Constant

6.1.3 Frequency step response.

The aim of this test is to show the step response due to a step in the frequency order reference.

Fig. 8 shows a change of the frequency reference from 48 Hz to 52 Hz. The first curve is the frequency step response and the second curve from above is the power order to the converter. The converter reduces the power transmission and the synchronous generator will then increase its speed due to the reduced load.

Fig. 9 shows a change of frequency from 52 Hz to 48 Hz. The first curve is the frequency step response and the second is the power order to the converter. The converter increases the power transmission that leads to a reduced speed of the synchronous machine. While the machine inertia has an inertia time constant of 3.3 [s], the speed of change will be in the same order. The converter power transfer is limited to the direction from the synchronous generator, to prevent that the converter feeds power into the synchronous generator during the speed increase.

6.1.4 Steps in power to the synchronous machine.

The aim of the test is to show the frequency response due to a power change in the synchronous generator.
Fig. 10. Steps in power to the generator. The frequency scale is 3 Hz/div and the power order scale is 100 kW/div.

The first case is a load change from 150 kW to about 1 MW and the second is a change back again from about 1 MW to 150 kW. The frequency deviation during the operation is less than 0.3 Hz. The power ramping in the machine is at its maximum rate.

6.2 Operation with a network without own generation

One of the basic features of a VSC converter is its ability to feed power into an a.c. system with no other generation. The converter will alone control the frequency and the a.c. bus voltage and consequently operate as a generator with the active power fed from the d.c. line. The purpose of the tests were to verify the following;

- Start-up of the converter with or without a.c. auxiliary power.
- Both manual and protective transfer of power flow from an a.c. feeder to the converter.
- Synchronisation and reconnection of an a.c. feeder to an a.c. system fed by the converter.
- Performance at faults in the a.c. system.

The configuration of the system was as shown in Fig. 11.

Fig. 11. System at isolated operation

The 10 kV bus at Hellsjön substation is normally fed from a 50 kV a.c. line through transformer T2. The HVDC converter is also connected to the same bus. The active power flow can be either to or from that bus via the d.c. line to the converter at Grängesberg 10 km away. The load along the a.c. line can be fed from either station by closing breaker 3 or 13. The available loads in isolated operation are approximately 700 kVA in Hellsjön and 1.5 MW in Grängesberg.

The tests described below were performed at Hellsjön. After these tests the power direction was reversed and Grängesberg operated isolated, but at a higher load than at Hellsjön.

6.2.1 Start-up of the converter with or without a.c. auxiliary power

The d.c. side is first energised from Grängesberg by closing the a.c. breaker. Switches along the d.c. line are closed which means that the converter at Hellsjön is energised on the d.c. side. The converter at Grängesberg is deblocked in d.c. voltage control mode. The converter at Hellsjön is now the only voltage source in that system and can therefore determine both the a.c. voltage and the frequency. This is provided by the converter control equipment which generates a reference voltage for the PWM with fixed frequency and an amplitude required to have nominal a.c. bus voltage on the a.c. terminals of the converter station.

In many applications it is likely that there will be no a.c. auxiliary power in the station before the converter is deblocked, which means that the converter has to start up without cooling equipment, and as soon as the converter has started, the valve cooling system can start up. The only auxiliary power required to start the isolated station is the power to the control equipment. Another feature which can be provided by the
converter is that the a.c. bus voltage can be ramped up in a smooth way to prevent transient overvoltages or inrush currents in transformers, for example. This test has been performed at maximum load at Hellsjön.

Fig. 12. Start-up of an isolated network

6.2.2 Both manual and protective transfer of power flow from an a.c. feeder to the converter.

The precondition for this test was that Hellsjön was fed from both the d.c. transmission and the transformer T2. In case the transformer is taken out of operation manually the sequence will start by increasing the power over the d.c. line, by a power or current order to the converter control, until the current in the transformer is close to zero. The transformer breaker (2) is opened and the converter operates alone feeding the isolated load. The converter control has to transfer from power/current control to a.c. voltage control. In this case a logical signal can be used to order a transfer to a.c. voltage control mode. The transfer is very smooth as there is only a minor change in the power flow. However, detection that the a.c. system is isolated must be general and cover cases where the isolation occur far away from the converter. A criterion within the control equipment has also been used to order transfer from current control to a.c. voltage control. In this case it must be a small disturbance in the a.c. bus voltage which is used to detect the fact that the system is isolated.

Fig. 13. Transfer from active to passive network. External order to transfer to a.c. voltage control

With the same precondition as above but the power flow in the converter is low. If a protection will trip the transformer breaker the power flow has to be transferred over to the converter. This means that there will be a transient voltage drop on the a.c. bus until the power flow in the d.c. line has increased so that the prefault level is restored into the a.c. bus. Then normal a.c. bus voltage will be restored.

Fig. 14. Transfer from active to passive network. Automatic order to transfer to a.c. voltage control.

The tests demonstrated that the converter can, with a minor transient, take over the required power supply to an a.c. network if all the other generators are tripped.

6.2.3 Synchronisation and reconnection of an a.c. feeder to an a.c. system fed by the converter

The converter feeds the isolated a.c. system and the transformer feeder is now prepared to be connected again. To allow this operation the voltage generated by the converter and the voltage on the transformer terminals have to be synchronised. This can be achieved by altering the frequency reference for the converter. When the two voltages are synchronised the transformer breaker (2) can be closed. When the transformer and the converter are connected to the same bus, the converter can no longer alone determine the a.c. bus voltage and will therefore switch back to normal power/current control. This sequence is manually ordered and is similar to synchronising and connect an a.c. generator. All the required power in the a.c. system was provided by the converter before
the transformer was connected, the transfer can therefore be very smooth.

6.2.4 Protection co-ordination in a passive a.c. distribution system fed by a VSC.
A VSC can be regarded as a three phase voltage source which has the ability to change the output three phase voltage quickly and independently. The behaviour of the a.c. distribution system will entirely depend on the control strategy of the VSC.

Overcurrent condition
In a passive network the a.c. bus voltage is proportional to the current injected into the system by the converter. The current order to the converter is generated by the a.c. voltage control. In case of a a.c. system fault the impedance decreases and consequently also the a.c. voltage drops. The a.c. voltage control increases the current order but it must be limited to maximum turn-off capability for the valve. As soon as the fault has been cleared by tripping the faulty line section the impedance in the system increases and the current order to the converter must be reduced to prevent an a.c. overvoltage.

Normally maximum current capability for the VSC converter is determined by the requirements for steady state operation. This means that the current overload capability is very limited. If the loads are protected by overcurrent protection or fuses, the rated current for the load should be low enough compared to the converter rating to ensure safe isolation of the faulty part of the system. In case of a relatively large load compared to the converter rating, impedance protection is recommended.

A consequence of the described properties is that settings for overcurrent protections and fuse ratings can be selected lower without jeopardising the security against false operation of the protection. The a.c. voltage can also be ramped up to prevent inrush currents.

AC system faults with no overcurrent
In cases where the fault will not cause any overcurrent in the system, such as single phase to ground faults in an impedance grounded system, the VSC will continue to operate with a.c. bus voltage control mode. It is very similar to the conventional distribution network supplied by a.c. generators or bulk power networks. In such cases, conventional earth fault protection systems can be used with the detection of zero sequence current or voltage or both.

6.2.5 Performance at faults in the a.c. system

The basic performance of the converter at an a.c. fault which results in low a.c. bus voltage is that the converter increases the output current up to the current limit for the valve. During this time the faulty condition will be detected by a protection, overcurrent or impedance protection. The protection will trip the a.c. breaker and at the first current zero crossing the fault is disconnected and the converter has to rapidly reduce the current to avoid a.c. overvoltage when the system recovers. The worst condition for this case has been tested in the Hellsjön VSC installation, which means an a.c. fault when the converter is feeding a light load.

The first fault applied was a three-phase short circuit on an outgoing a.c. line. The converter feeds the isolated a.c. system, then the line breaker (4) is closed with a three-phase fault on the a.c. line. The a.c. voltage drops and the converter current increases up to its limit and then the protection operates and clears the fault. When the fault has been cleared the converter limits the a.c. bus voltage during the system recovery by fast reduction of the current. The fault was detected by a standard overcurrent relay

A similar test was performed with the fault instead applied on the 50 kV side of the transformer T2. The converter was feeding the isolated a.c. system and then the a.c. breaker (2) was closed.

![Breaker 4 current](image)

![AC bus voltage](image)

Fig. 16. AC system fault. Fault clearing with overcurrent protection.
In this case an impedance protection was installed on the 10 kV side of the transformer. This means that the protection should be selective not to operate for the inrush current but operate for the relatively low fault current. The fault current and fault clearing are similar to the case described above.

Fig. 17. AC system fault. Fault clearing with impedance protection.

7. CONCLUSION
For the first time an HVDC transmission based on Voltage Source Converter has been built, tested and operated. The experience from field tests with both active and isolated a.c. systems shows that converters with high frequency PWM is feasible to use for small scale HVDC. The VSC converter will also also provide the a.c. system with beneficial properties.

The converter does not need many components compared to traditional HVDC. It does not even need a transformer, only phase reactors and fixed high pass filters. Despite this, active and reactive power can be controlled independently and extremely fast. The short circuit power of the receiving as network is of no importance. It is possible to operate even with receiving a.c. networks having no rotating machines.

With the rapid development of semiconductors and control, one can foresee that HVDC using VSC converters will soon become a very interesting new option for the transmission of power.

8. REFERENCES
Article: