HVDC Light, a tool for electric power transmission to distant loads

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SUMMARY
HVDC Light is a newly developed technology for electric power transmission by HVDC based on Voltage Source Converters. This has many interesting characteristics that make it a very promising tool for transmission of electric power to distant loads, where no other transmission is possible or economic. The technology is presented here and its application to a pilot transmission, which is now operating in a commercial network since March 1997. Special emphasis is given to the possibility to serve the loads in a connected AC network without own generation.

New DC power cables based on a modified triple extrusion technology and a specially designed DC material have been developed. DC power cables with ratings 2 x 25 MW at 100 kV can be accomplished weighing only 1 kg/m per cable. Such cables can be installed at low cost by e.g. ploughing technique and aerial cabling. Larger cables can transmit much more power.

Voltage Source Converters together with these cables constitute an excellent tool for providing power to any distant location. Thereby the advantages of a large network can be brought to basically any place. A few applications are presented to show this. The state of the art considers ratings in the range of 1-150 MVA and with direct voltages up to around ±100 kV. The converters will be based on a modularised concept for serial production of standard sizes in order to keep size, delivery time and cost low.

Keywords: HVDC, Voltage Source Converters, transmission, PWM, distant loads

For the future both power and voltages will increase and extension to pure DC networks will be possible.

1. INTRODUCTION
The HVDC technology has been successful to connect AC networks that for technical or economical reasons cannot be connected by AC transmission.

The present technology uses circuits with PCC (Phase Commutated Converters) and is based on thyristor valves with semiconductor devices that can be turned on by a positive gate pulse when the main voltage is positive. To turn off the thyristors need a negative voltage across the main terminals. This is normally achieved by commutating the current to the valve in the next phase.

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

These weaknesses can be overcome by using Voltage Source Converters (VSC) which have now been developed for high voltage application. The Hellsjön Project is the world’s first VSC HVDC transmission. It is rated 3 MW and ±10 kV DC. The link is in operation in a commercial network since the beginning of March 1997 between Hellsjön and Grängesberg in central Sweden on a 10 km long de-commissioned AC line. The operation experience has been entirely positive. The transmission 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.

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2. VSC TECHNOLOGY AND PULSE WIDTH MODULATION (PWM)

In industrial drives the PCC (Phase Commutated Converter) technology which is 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 need 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. In HVDC-applications it could then be of interest to use VSC technology in order to supply passive networks, that is areas which lack rotating machines or networks that does not have enough power in the rotating machines (too low short circuit power).

By use of higher switching frequency components it is possible to use Pulse Width Modulation (PWM) technology. Then 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 it is not necessary to have a transformer for the functioning of the converter. See figure 1.

Figure 1 shows one phase of a VSC converter using PWM

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 instantaneous. Hereby PWM offers the possibility to control both active and reactive power independently.

This makes the VSC using PWM 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 2 shows the PWM pattern and the fundamental frequency voltage in a Voltage Source Converter

3. 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 have not been semiconductor components available that have been good enough for the task.

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 and can be 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 components for the voltage of 2.5 kV has recently become available in the market 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 an interesting component for small scale HVDC applications.

4. CONVERTER OPERATION PRINCIPLES

The converter consists of a six-pulse bridge, two-level, with series connected IGBT:s in each valve, or can be a three level converter.
Every IGBT is provided with an antiparallel diode. 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.

The main advantages of converters with IGBT:s 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. The converter firing control calculates a voltage time area across the converter reactor to control the current through the reactor to the reference value. The current order to the controller is calculated from the set power/current order or the DC voltage control, and a corresponding PWM pattern is generated.

The active power flow between the converter and the AC network is controlled by changing the phase angle ($\delta$) between the fundamental frequency voltage generated by the converter $U_g$ and the AC voltage on the AC bus. The power is calculated according to the formula assuming a lossless reactor:

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

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 $U_g$.

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

The transmission starts up by energising the two stations separately. The AC breakers are closed which means that the DC busses are energised 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 and when the other converter is deblocked 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 work 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 would mean that the DC voltage in the system will rapidly change. To achieve power balance one of the stations is controlling the DC voltage. This means that the other station can set any active power order within the limits for the system. The voltage controlling station will 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.
5. CABLES

The new HVDC Light cables have insulation of extruded polymer. Until now, the cables used for HVDC transmission and distribution, have been paper insulated cables, low pressure oil filled cables (LPOF) or mass impregnated non draining cables (MIND). There are several drawbacks with these designs. The LPOF cable needs auxiliary equipment to maintain the oil pressure and can not be easily installed. The MIND cable has limitations in the operating conductor temperature. There are of course also environmental oil spill concerns that are associated with the LPOF cable. Paper insulated cables are not feasible for aerial cables because of sensitivity to repeated bending. HVDC Light cables are laid in pairs with antiparallel currents and thus eliminating magnetic fields.

In HVAC there has been a change of technology going from paper insulated cables to extruded, mostly XLPE cables. The preference of extruded cables also for applications in HVDC has been obvious for a long time. Several reports have been published where XLPE has been tested for HVDC applications but without success. One reason has been the existence of space charges in the insulation leading to uncontrolled local high electric fields causing dielectric breakdowns. Another reason has been uneven stress distribution due to temperature dependent resistivity causing overstress in the outer part of the insulation. This HVDC Light cable development work with the objective to type test an extruded HVDC cable, was initiated a couple of years ago. It has now resulted in an extruded cable for HVDC that is an important part of the HVDC Light concept and opens new opportunities for future power transmission and distribution.

The extruded HVDC cable that has been developed and which is also in short lengths included in the Hellsjön project is of a design shown in Figure 4. The design can transmit at least 2 x 25 MW at 100 kV and weighs only 1 kg/m. It is a triple extruded cable with a 95 mm² aluminium conductor and 5.5 mm insulation thickness. The design also includes a copper wire screen with a cross-section of 25 mm² due to standard reasons. The outer sheath is made of HDPE making this cable easy to handle and to install for instance using a ploughing technique.

In order to achieve the necessary performance of the extruded cable, a special material had to be developed as well as modifications to the cable extrusion process. The voltage breakdown values of the cable up to now have been difficult to establish. The reason is breakdowns at the test terminations since the voltages are very high and in combination with the small outer diameter of the cable, the electrical stresses in the termination become the limiting factor in testing. The short term breakdown voltage for this type of cable can therefore at present only be said to well exceed 600 kV. A long term test with daily load cycles to qualify 100 kV in continuous operation is currently in progress.

6. PRACTICAL FEATURES OF THE HVDC LIGHT

The technical characteristics of the VSC make it feasible for a variety of transmission applications for which conventional HVDC is unable to compete today, either from economical or from technical point of view.
The VSC has a simple and straightforward circuit solution. The technical simplifications such as small filters, no transformers, less switching equipment and simple civil works contribute to small footprint, robust mechanical design and easy handling. By this the converter equipment can be placed in simple module type housings, see Figure 5. A VSC converter 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 opportunities to preinstall the equipment at factory and run highly complete tests before shipment. It will easily lend itself to a considerable degree of standardisation and to installations which can be relocated, when needed.

The plant production process will be based on a set of standardised sizes with module drawings ready on the shelf. The need for engineering will 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. Automonitoring of status so that faults will be automatically detected and alerted will give the possibility to rapidly exchange faulty equipment.

7. DISTANT LOAD APPLICATIONS

Electrical systems are mostly built as meshed networks with multiple interconnections between various loads and generation stations. In such a network the power can be exchanged via different routes and the cost of power can be considered common to the all loads in the network. There are, however many places, small cities, villages, mines etc., that are located far from any network. Such a place we call a distant load. The supply of power to a distant load can be made by a radial transmission from a meshed network or by local generation.

For small loads below 150 MW, local generation has been necessary, for distances beyond what has been possible to reach with an AC transmission. Traditional HVDC has not been cost effective in this power range, because it did not have the technical possibilities to feed power into an isolated load without synchronous machines. HVDC Light will now provide an excellent alternative for power transmission to small distant loads (see Figure 6).

The characteristics that make HVDC Light suitable for feeding distant loads are particularly:

- It can feed power into an isolated load without any synchronous machines, generators or compensators.
- The active and reactive power can be controlled independent of each other in an HVDC Light station. A receiving station can control both the voltage and the frequency of the power fed into a network in the same way as a generator. Electrically this corresponds to connecting the load to a close generator.
- The current from the converter into the load is limited by the current control of the converter. Thus the short-circuit current from the converter is limited and no short-circuit contribution is necessary.

Long distance AC transmission with overhead lines has to go to higher voltages with increasing distances and at long distances it becomes technically impossible or economically too costly. In many cases local generation is the only possibility and if no natural, local generation resources exists the natural choice has been diesel generators, which are run by high cost fuel.

DC transmission has no natural limitation to distance. It is limited by which losses can be accepted and if losses are too high a larger conductor area may be used. Thus even for very long distances an economic optimisation of the conductor area with acceptable transmission losses could be reached.

The newly developed extruded DC cables are very effective with regard to direct voltage capacity and thereby give possibilities for high power compared to a similar AC cable. Thus these cables together with the converters will make the HVDC Light concept a low cost alternative for long distance transmission to small loads compared to AC cables but also compared with AC overhead lines.

It is possible to design for converters in the range 1-150 MVA and with voltage ratings up to ±100 kV. By the HVDC Light concept DC transmission will economically extend in rating to a few MW thanks to the reduced costs of converters and cables in the low power range and the possibility to operate without synchronous machines in the receiving end.

In many places overhead lines meet objections from environmental point of view. The HVDC Light concept will now be the natural alternative to make transmission of power more environmentally friendly.

Many times there is a possible generation resource, that could be developed for a distant load. Due to transmission difficulties, technical or economical such a development was not realised. Together with an HVDC Light transmission the possibilities may now improve so that it becomes economical to give the distant load its own generation from a distant source. Examples of such generation are small
hydraulic generators, wind mill farms and solar power.
By use of a block connection from a small hydraulic generator to the HVDC Light converter it would be possible to take advantage of the converter characteristics and design the generator for a higher frequency and thus decrease weight and cost of the generator. Another possibility is to use an asynchronous generator. A variable frequency can be used for wind mills too, by which they can operate always at the speed that gives maximum power.

8. CONCLUSIONS
The development of power semiconductors, specifically IGBT:s and extruded DC cables led to that small scale HVDC in combination with cables can offer a number of new applications to serve the needs of utilities.

Such installations have several characteristics that make them very attractive.
- Opportunity to transmit small scale power long distances via cable
- Opportunity to connect to passive load
- Separate control of active and reactive power
- No contribution to short circuit currents
- No need of fast communication
- Low complexity thanks to few components
- Opportunity to operate without transformers
- Small and compact

In many cases this will be a very interesting alternative to local generation or conventional AC transmission in order to provide power to distant locations.

9. REFERENCES
Article:

Figure 6 shows small scale generation application for distant loads