HVDC Light™ and development of Voltage Source Converters

K. Eriksson, *ABB Utilities*

***Abstract*- On March 10, 1997 power was transmitted on the 3 MW HVDC Light™ transmission between Hellsjön and Grängesberg in central Sweden. This implied that Voltage Source Converters and series-connected Insulated Gate Bipolar Transistors (IGBT:s) were for the first time being used for an HVDC transmission in a real network. Operation and System Tests proved that the properties that have been discussed since many years regarding VSC HVDC are really in existence such as independent control of active and reactive power, operation against isolated ac networks with no generation by its own, very limited need of filters and no need of transformers for the conversion process. A first development step for a new technology was taken and the impression was that this technology would play an important role in the future expansion of electric transmission and distribution systems.**

Since then extensive testing was performed and development continued for a commercial concept. A modular design for a first generation was established and has been used in four transmission installations in various parts of the world. These installations have power ratings from 8 to 180 MW, with the biggest modular unit of 60 MW and a direct voltage of +/-80 kV. Operational experiences from these links have confirmed the above mentioned expectations on the controllability properties. In addition the installations have showed to be environmentally sustainable.

At the same time the development continued towards higher converter ratings and voltages and converters for up to 350 MVA and +/-150 kV design were put into the market. Two projects of this design have been undertaken one in US and one in Australia. The market interest is high. The majority of HVDC Light™ links so far in operation or under construction have been motivated for network interconnection or infeed of wind power. These applications and others will be described and exemplified.

The development on semiconductors is progressing rapidly and hopefully more powerful IGBT's will soon be available. Converter ratings could then continue towards higher power and voltage or be utilized for concepts where lower losses are achieved.

Keywords: Controllability, Development, Electric power transmission, HVDC Light™, IGBT, network interconnections, operational experiences, Voltage Source Converters

I. VSC CONVERTERS WITH 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 on and off by controlling the semiconductor valves, 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 and reduce the filter size. Then the converter with simple topology can be used, as there is no need for sophisticated phase shifted sub-converters. The ac-voltage in inverter mode 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 figures 1and 2.

On the other hand, when an AC voltage is applied outside the reactor the anti-parallel diodes will act as an uncontrolled rectifier. By PWM switching between the valves the direct voltage can be boosted up to a level, that would be suitable for proper control of direct voltage (active power) and of reactive power.

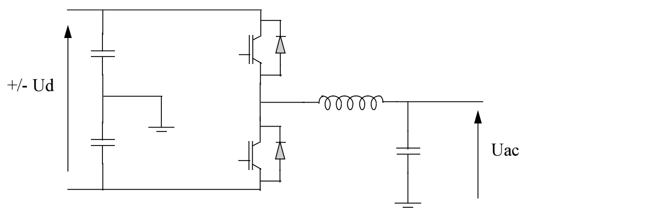

Figure 1 shows one phase of a VSC converter using PWM

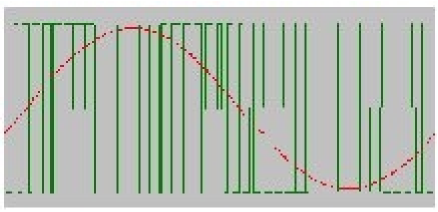

Figure 2 shows the PWM pattern and the fundamental frequency voltage

K. Eriksson is with ABB Utilities AB (e-mail kjeller.eriksson@se.abb.com

II. THE HELLSJÖN PROJECT

Development work on VSC converters has been going on for a long time within ABB. During this development it was realized that the IGBT should be 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. By this series connection of many semiconductors with good voltage distribution even at switching frequencies in the kHz range should be possible. To fulfil that 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.

In 1994 the development on VSC converters was concentrated into a project to put two VSC converters for small scale HVDC based on IGBT's 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 50 kV back-up ac line between Hellsjön and Grängesberg, 10 km long in central Sweden was made available for the project. The transmission rating is 3 MW, somewhat above the hydro generator at Hellsjön and operates with ±10 kVdc. The converter stations are connected into an existing 10 kV ac network.

During the development of the project the various characteristics and behaviors of VSC converters, PWM control, IGBT valves etc. were tested in digital and simulator simulations, a low power test circuit and 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. March 10, 1997 power was transmitted between Hellsjön and Grängesberg in the Hellsjön Project, the world's first VSC HVDC transmission. It proved to be easy to test, install relocate and operate and we call it HVDC Light™.

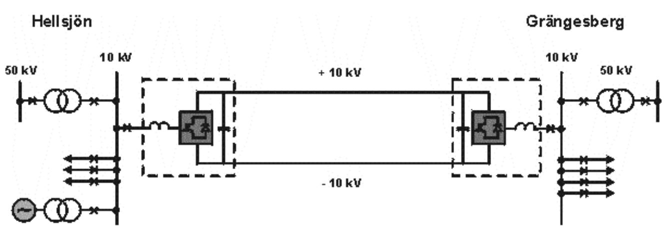

Figure 3 shows the VSC HVDC Light™ Transmission between Hellsjön and Grängesberg

III. TESTING IN HELLSJÖN

Before delivery to site the complete system was tested with full rated voltage (10 kV a.c. and ±10 kV d.c.) and current. Full converter operation was tested with the two converters connected and operated in round power mode. 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.

Thanks to the factory testing of the complete system the commissioning at site was very fast. Each station was properly tested operating as a SVC as, a single unit independent of the other station.

Commissioning included measurements of the following properties of the converters.

- Sound power level. 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. The measured RI meets 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. The harmonic distortion level (THD) on the a.c. side at Hellsjön has been measured at various load conditions of the converter. The measured total harmonic distortion up to 3 kHz was 3.8 % , target level 5.0 (Electra 149, Aug. '93 page 75 table I) for bus voltages below 69kV.

As part of the testing a large system test program was carried out. This included:

– Radial interconnection of synchronous generator and converter with the aim of testing the feasibility of feeding a VSC converter from an isolated synchronous generator. The operation mode was constant power control and a.c. voltage control at the synchronous generator and frequency control at the converter. One of the tests made were a change of frequency from 52 to 48 Hz, to show how this resulted in an increase of the power order to the converter to achieve a reduced speed of the synchronous machine.
– Operation with a network without own generation testing the ability of a VSC's characteristics for this operation mode. 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.
  - Synchronization and reconnection of an a.c. feeder to an a.c. system fed by the converter.
  - Performance at faults in the a.c. system.
  - As examples of these tests we show below the start up of an isolated network from the HVDC Light™ transmission and the behavior at fault clearing with impedance protection.

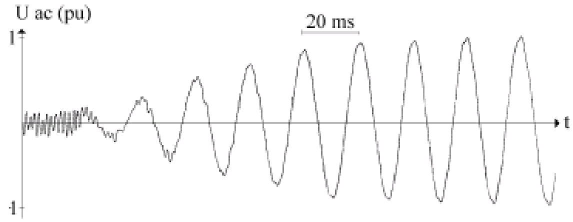

Fig 4 Start-up of an isolated network

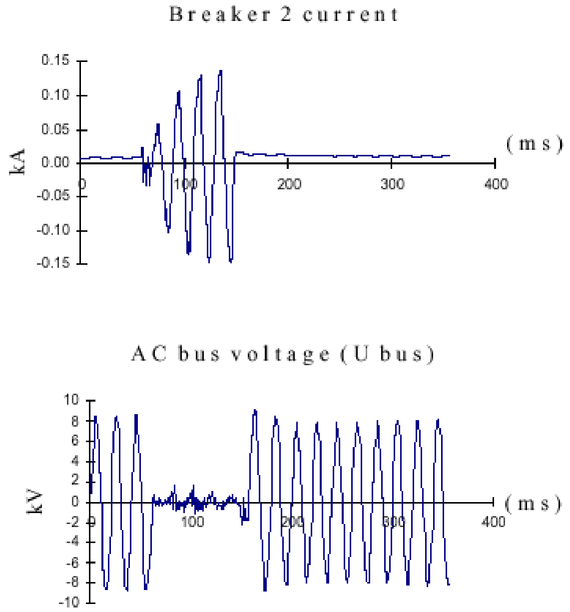

Fig 5 Ac system fault. Fault clearing with impedance protection

IV. HVDC LIGHT™ CABLES

The HVDC Light™ polymeric cables system is qualified for two voltage ranges, i.e. Uo = 80 kV (Um = 88kV) and 150 kV (Um=165 kV). The qualification tests have comprised long term tests and Type Tests successfully performed. The amount of commercially delivered HVDC Light™ cables is now in excess of 500 km, 250 km bipolar route length for the three projects Gotland in Sweden, Tjaereborg in Denmark and Directlink in Australia.

Compared with traditional paper insulated cables, the polymeric cable immediately shows up to advantage because of its excellent mechanical flexibility and strength, leading to new applications

Deep-Sea Cables. Submarine HVDC Light™ cables can be laid in very deep waters and on rough bottoms. The very robust polymeric insulation material can withstand high forces and repeated flexing. The HVDC Light submarine cables are also more suited for deep water than polymeric submarine cables for AC applications. This is because single or double galvanized steel wire armour can be used for DC current whereas non-magnetic and less strong armours normally are used for AC cables

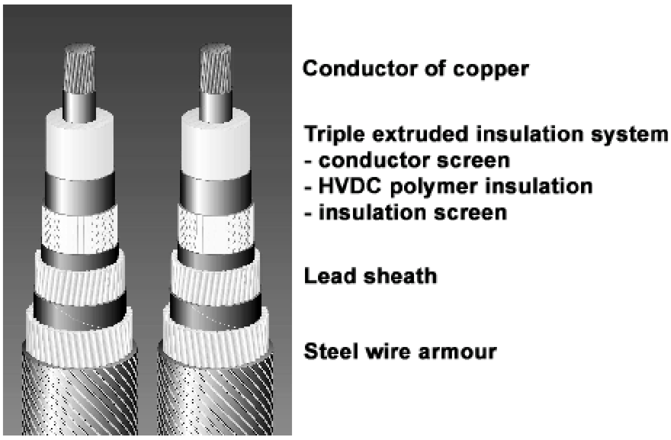

Figure 6 shows 10 – 600 MW deep sea HVDC Light cable

Aerial Cables. HVDC Light™ cables can be used as overhead cable in the same way as other polymeric cables, with the difference though that a DC bipole utilizes two cables and am AC three-phase system utilizes three cable (or cores).

V. HVDC LIGHT™ DESIGN ASPECTS

It was decided to base the HVDC Light™ design on a modular concept with a number of standardized sizes, 10-100 MW. The design was based on two-level converters up to around +/-80 kV. Most of the equipment should be installed in enclosures at the factory. Tests should be made there, to make the field installation and commissioning short and efficient. The standardized design allowed for delivery times of around 18 months.

The stations are compact and need little space, a 65 MVA station occupies an area of approx. 800 sq. meters as can be seen from the below Gotland Light station layout. A 250 MVA station would require around 3000 sq.metres

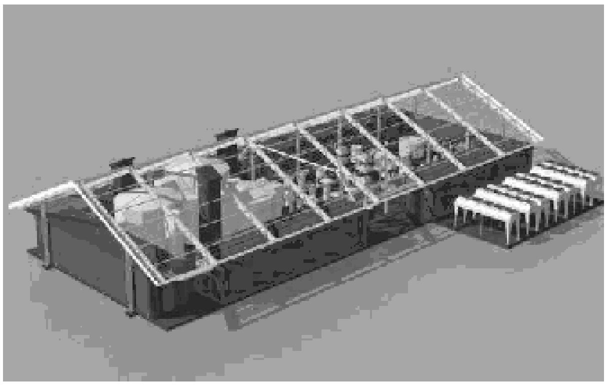

Figure 7 Model of the Gotland HVDC Light™ station 18x45 m.

The appearance can easily be adapted to local environmental requirements for easy permitting. The HVDC Light™ technology itself is designed to be environmentally friendly. Since power is transmitted via a pair of underground cables there is no visual impact along the transmission. The balanced voltage to ground eliminates the need of an electrode. Thus there is no ground current and consequently there is no electromagnetic field from the cable pair.

The stations are designed to be unmanned and are in principle maintenance free. Operation can be carried out remotely or could even be automatic based on needs of the interconnected AC networks.

VI. HVDC LIGHT™ EXPERIENCES

During 1999-2000 four HVDC Light™ transmissions were taken into operation as shown in the table below:

Project	Country	Dist km	Rating MVA	Start operation	Main motive
Gotland Light	Sweden	70	60	Nov.1999	Infeed wind power
Direct-Link	Australia	65	3 x 60	June 2000	Trading of power
Tjaereborg	Denmark	4	8	Sept. 2000	Demo wind power infeed
Eagle Pass	USA	Btb	36	Nov. 2000	AC volt control

Some of the general experiences from the early operation of the Gotland link are related below:

- HVDC Light is a necessary installation from a power quality and dynamic stability point of view already at today's level of installed wind power production. The large variations in reactive power demand from the windmills has shown to be compensated by the HVDC Light™.
- A new generation control system as all new systems caused some initial outages and has been the reason for most occurring faults. In first hand this refers to communication between units, that did not work in all situations
- HVDC Light is also simple to switch over to and operate in special modes. One such operation mode is the standby mode in the Bäcks station during no transmission operation. When needed the Bäcks station works as a normal SVC within one cycle.
- Although a controlled active power transmission DC system the general experience from the dispatch center is that it works better and with less stresses than an ordinary AC system. Together with control functions it has been very simple to automatically handle normal variations in production and loads.
- During faults the voltage dips have been reduced in all parts of the grid, which has reduced load rejection problems that occurred before the installation of the HVDC Light.

Another example of the controllability of the HVDC Light™ is the use of it for trading as is shown by the below power exchange records from Directlink during a week in December 2000.

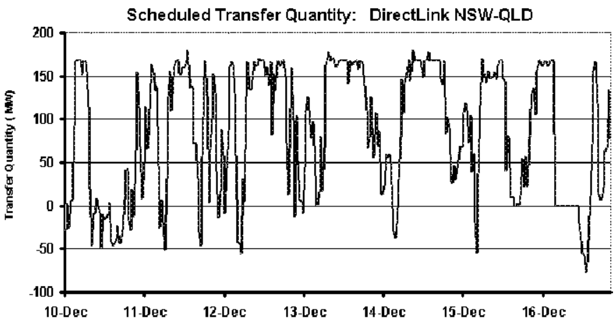

Figure 8 Power transmission by the Directlink.

VII. THE SECOND GENERATION

In the meantime of completing the above projects challenges with higher transmission ratings appeared and a new step in the development was taken by increasing the power to above 300 MW. This was achieved by going to higher voltages, +/- 150 kV, high current IGBT's and a three-level configuration. This also required a development of the mechanical design to keep the compactness of the converters and stations.

This second generation has shown a great deal interest and so far two links are undertaken to be in operation during 2002:

- The Cross Sound Cable project is a 40-km HVDC Light transmission between New Haven, Connecticut and Shoreham on Long Island outside New York. It will supply transmission of electric energy to Long Island. The rating is 330 MW with possibility of both local and remote control. The link is developed by Transenergie and the customer is Long Island Power Authority and United Illuminated.
- Murraylink is a transmission between Red Cliffs, Victoria and Berry, South Australia. In the same way as Directlink it will link regional electricity markets and will be a non-regulated project based on market based returns. In the same way as Directlink it will use the ability of the HVDC Light technology to control power flow over the facility. The Voltage Source Converter terminals can act independently of each other to provide ancillary services (such as var support and voltage control) in the weak networks to which it is connected.

Of the projects, that were so far decided two are for infeed of wind power, Gotland and Tjaereborg and the other four represent various kinds of interconnections of the traditional

HVDC type, but at lower ratings. From the day HVDC Light was presented interest for the new technology was high and it has continued that way both for the above types of applications and for other applications. New types of applications which are discussed in conferences etc are for example feeding of small networks, feeders to platforms and infeed to cities.

VIII. FUTURE DEVELOPMENT

Development of both components and technology are continuing and there is a high interest in finding solutions for both higher ratings and more effective converters.

One expectation is to extend the IGBT ratings towards higher voltage rating to achieve the high voltages, that are needed for transmission distances with fewer components and it seems that a next step for replacing to-days 2.5 kV components could be at least 4.5 kV.

Another expectation is to find converter configurations that can improve rating and losses. This was the reason to use three-level converters for the latest projects to achieve the higher ratings mentioned above. Operation security with the three-level converters will basically be the same as for the original two-level converters.

IX: References

[1] Eriksson K, Graham J,: HVDC Light™ - a transmission vehicle with potential for ancillary services; SEPOPE2000 Curitiba, Brazil, May 2000.

[2] Asplund G, Eriksson K, Hongbo J, Lindberg J, Pålsson R, Svensson K: DC transmission based on Voltage Source Converters. Cigre; Paris August 1998

[3] Axelsson U, Holm A, Liljegren C, Åberg M, Eriksson K, Tollerz O,: The Gotland HVDC Light™ project – experiences from trial and commercial operation; CIRED 2001, Amsterdam, Netherlands, June 2001.

[4] Skytt A-K, Holmberg P, Juhlin L-E,: HVDC Light™ connection of wind farms, II Int. Workshop on Transmission Networks for offshore wind farms; Stockholm March 2001.

[5] Eriksson K: Operational experience of HVDC Light™. 7th International Conference on AC-DC Power Transmission, London, November 2001.

Kjell Eriksson, M.Sc. EE, PMP, was born in Sweden March 31, 1939. He graduated from the Stockholm Royal Institute of Technology 1964, (Master of Science) in Electric and Electronics Engineering. He worked with the Swedish Defense Research Institute 1963-1965.

In 1965 he joined ASEA to work with Development and design of HVDC controls including analysis of dynamic behavior of HVDC systems 1965-1971. 1971-1979 Marketing and Sales of HVDC projects with task as coordinating proposal engineer for various large project proposals including Itaipu in Brazil. 1979-1991work with the Itaipu HVDC transmission with tasks as Head of Systems Studies in the ASEA-Promon HVDC Consortium Project Team, Project Manager for ASEA Sweden Project Team for the Itaipu project and Project Director for the ASEA-Promon HVDC Consortium Project Team. 1992-1996 Project Manager for the Baltic Cable HVDC Project for ABB Power Systems' supply. Since 1996 working as a project manager with technical development and marketing for the HVDC Light technology. Kjell Eriksson is a member of Cigre.