OPERATIONAL EXPERIENCE OF HVDC LIGHT™

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1. SUMMARY

HVDC Light™ is an electric power transmission technology based on Voltage Source Converters with Pulse Width Modulation and modern HVDC cables. This type of converters with modern power electronics has interesting characteristics based on separate and fast-acting controls of active and reactive powers. The technology is well suited for connection of networks that otherwise are difficult or impossible to inter-connect. It's suitability is based on accurate control of the transmitted active power and independent control of the reactive power in the connected AC networks.

HVDC Light™ is designed at standard units between 10 and 300 MW and are built in transportable housings. This together with the above technical characteristics make them suitable for various applications of power transmission, such as exchange of power between networks, infeed of wind power to a network or as a feeder to an isolated load.

There are four HVDC Light™ transmissions in operation in the world: one each in the countries of Sweden, Denmark, Australia and US. The HVDC Light™ links so far in operation or under construction have been justified for network interconnection or infeed of windpower. The speed and accuracy of both active and reactive controls have been used in customised ways in each of the above projects and is a key to success for HVDC Light™ projects.

As the first project, the Gotland Light in Sweden started operation in November 1999 and the others came along during 2000. The operational experiences for the Gotland Light, Tjaereborg, Directlink and Eagle Pass projects regarding the use of the controllability of HVDC Light™ projects is presented.

2. VOLTAGE SOURCE CONVERTERS WITH PULSE WIDTH MODULATION

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 is that in a VSC the current can be switched on and off by controlling the semiconductor valves. Thus there is no need for a network to commutate against.

By use of high switching frequency components e.g. IGBT's it is possible to use Pulse Width Modulation (PWM). Thus it is possible to create any phase angle or amplitude (within 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.

Reactive power generation and consumption of an HVDC Light™ converter can be used for compensating the needs of the connected network within the rating of a converter. The combined active/reactive power capabilities are most easily seen in a P-Q diagrams, like the one below.

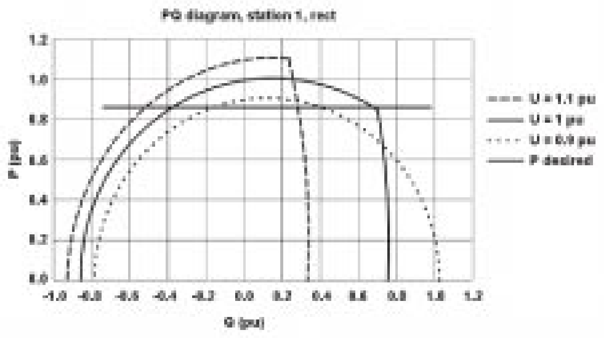

Figure 1 Shows a possible P/Q characteristics of an HVDC Light™ station (positive Q is fed to the AC network).

3. HVDC LIGHT™ DESIGN ASPECTS

The HVDC Light™ design is based on a modular concept with a number of standardized sizes, 10-300 MW. Most of the equipment is installed in enclosures at the factory. They can be tested there, which makes the field installation and commissioning short and efficient. The standardized design allows 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.

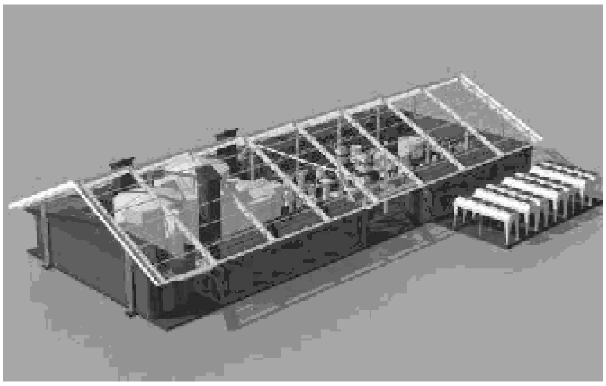

Figure 2 Model of the Gotland HVDC Light™ station 18x45 m.

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.

4. HVDC LIGHT™ TRANSMISSIONS IN OPERATION

March 1997 the Hellsjön transmission, rated 3 MW, +/-10 kV over 10 km entered into operation to demonstrate the feasibility of the technology to operate in a network. It used merely setting controls for active and reactive currents. Yet it showed to have quite interesting characteristics for supporting the networks.

The Gotland HVDC Light™, 50 MW over 70 km is bringing wind power from southern Gotland to the center of the island. It is in operation since November 1999. The basic controls are changed to power controls of active and reactive powers. In the Gotland HVDC Light™ transmission the reactive power capabilities are used to control the AC voltages of the networks connected to the converter stations.

Directlink is a 180 MVA HVDC Light™ project that links the regional electricity markets of New South Wales and Queensland. Directlink will be a non-regulated link, operating as a generator by delivering energy to the highest value regional market and directly participating in the spot market. The ability to control power flow over the facility means that the capacity rights required for fully commercial network service are readily defined. The VSC stations can act independently of each other to provide ancillary services (such as var support) in the weak networks to which Directlink connects. The system has been in commercial operation since June 2000.

A DC feeder, using an 8 MVA HVDC Light™ link with VSC is in operation since September 2000 at Tjæreborg in Denmark to investigate and demonstrate how a DC feeder may be used to transmit power from wind farms to a receiving AC grid. It can operate as rectifier or inverter and at the same time absorb or supply reactive power to the AC network and is therefore suitable for connection of wind farms with induction generators.

The Eagle Pass HVDC Light™ Back-to-back, 36 MW controls the reactive power at each converter independently. In Voltage Control Mode, the AC voltage control may use all capability of the VSC regardless of the set power order. One of the converters may be connected to a passive network, i.e., a system without synchronous machines. The transmission has been in operation since November 2000.

5. HVDC LIGHT™ IN THE NETWORK

The HVDC Light™ links in operation have a common basic control design and then each one of them has its specific control features to act in its specific network environment. Thereby each one of them can give ample support to the connected AC networks.

5.1 Active power

An HVDC Light™ transmission can control the active power transmission in an exact way, so that the contracted power can be delivered when requested. The power transmission can be combined with a frequency controller that varies the power in order to support the network frequency controller. Spinning reserve in one network combined with free transmission capacity can be valid also for the network in the other end of the transmission.

This can be exemplified from operation characteristics of already operating HVDC Light™ transmissions.

The Hellsjön transmission was entered into the Swedish grid to demonstrate the feasibility of the technology to operate in a network and was not provided with any sophisticated controls, but used merely setting controls for active and reactive currents. Testing was however extensive. During testing it proved to be able to operate with variable frequency and also to provide frequency control, so that the power needed to keep the frequency control could be delivered.

On the Gotland network the introduction of an HVDC Light™ link permits the active power flow in the network to be controlled. Continuous calculation is considering both reactive compensation and active power flow and the optimization are made for the losses in the entire Gotland system. This makes the HVDC Light™ a very powerful tool for power flow control for the Gotland scheme.

Directlink is a 180 MVA HVDC Light™ project that will link the regional electricity markets of New South Wales and Queensland. Directlink will be a non-regulated project, operating as a generator by delivering energy to the highest value regional market. The HVDC Light™ technology advantages include that the flow of energy over the link can be precisely defined and controlled, so that the capacity rights required for fully commercial network service are readily defined.

Tjæreborg in Denmark is an 8 MVA HVDC Light™ link with Voltage Source. The VSC converter's ability to change the stator frequency of the induction generator within 30-65 Hz gives the possibility to optimize the power output from the wind turbine by adjusting the frequency in relation to the wind

5.2 Reactive power

The HVDC Light™ converters can provide reactive power and combined with a master controller, provide AC voltage control to the networks connected to the converter stations. Such an AC voltage control can also be used for improving the power quality by inclusion of flicker control. The following can be referred to the existing installations.

In the Gotland HVDC Light™ transmission the reactive power capabilities are used to control the AC voltages of the networks connected to the converter stations. With the verified speed of response the AC voltage control will be able to control transients and flicker up to around 3 Hz and other disturbances and keep the AC bus voltage constant. It is thus capable to relieve a considerable part of the wind power generated flicker from the AC bus.

The normal operation of the Tjaereborg link will be to use frequency and voltage control in the converter connected to the wind farm. The HVDC Light™ has the capacity to provide the reactive power necessary for the operation of the induction generators predominant in wind power generators.

The control scheme of the Eagle Pass HVDC Light™ back-to-back, 36 MW will control the reactive power at each converter independently. In Voltage Control Mode, the AC voltage control may use all capability of the VSC converter regardless of the power order set point.

5.3 Black start

In case of connection to a passive network, the HVDC Light™ transmission can provide control functions for active and reactive power, so that both voltage and frequency can be controlled from the converter station. This especially this provides possibilities for black start by control of voltage and frequency from zero to nominal. A transmission to such a passive network will give the same control possibilities as the connection of a generator. The use of black start capability has been tested and/or foreseen in some cases.

In Tjaereborg the black start capability will be used to start up the windmills by providing the reactive power necessary to the induction motors. In Eagle Pass one of the converters may be connected to a passive network, i.e., where no synchronous machine is connected to the network. In this case, the magnitude of the AC voltage will be controlled, as long as the converter valve current is below the permissible value and the station has black start capability.

6. EXPERIENCES FROM COMMISSIONING AND OPERATION

6.1 Gotland

Experiences from testing and early operation included measurements at steady state and a staged fault in the 10 kV network. The behaviour was analysed during fault cases and for several regulation mode shifts executed manually and automatically. The wind power generation has been analysed during faults including the possibility to trip wind power units when necessary. The unique power flow controllability within the AC network is utilised by means of the network master control including set point values calculated from an overall losses minimisation algorithm. The loss minimisation utilises reduced DC voltage at reduced power, which gives as a drawback a reduced reactive power capability. The voltage control consisting of the master control set point values, the flicker control due to wind power tower shadowing around 1.5 Hz and the transient voltage control during faults were analysed. It was observed that the voltage control of the HVDC Light™ reduced voltage and angle variations so that the wind power did not synchronise to the flicker and a separate flicker control may be unnecessary.

In a conventional AC system the asynchronous generation from windmills and with very low short circuit power, ratio of only 1.75 would have made the system basically impossible to operate. Changes in the power flow from the windmills would strongly influence the voltage in the windpower infeed station and result in a very sensitive and unstable system. With the HVDC Light™ it proved to be easy to operate and control. Operation showed a smooth handling of the power flow, control functions for voltage levels, reactive and active power settings in an optimum way that should have been difficult for an operator to achieve in a conventional AC application. Operation can be automatic even at the onset of the windmills with no significant stress to the system The experience shows that this operation is much simpler than utilising capacitor banks to control reactive power balance. One experience from the early operation has been a difficulty to restart the system from remote in connection with some failures that requires manual resetting in the control.

In the middle of 2000 an extensive test program was executed including various realistic operational modes. Dedicated measurements were performed during this period both within and close to the HVDC Light™ stations, in important network nodes and along the HVDC Light™ cables. Measurements of harmonics, flicker, EMC, voltage dips and power flows were recorded. Harmonics were measured at the 70 kV AC network side in both stations and also at lower voltages at the sending end station. The following values were recorded at 70 kV:

THD (%)	THD excl. h5 (%)	TIF	Station
1.5	0.6	26	Bäcks
1.3	0.9	12	Näs

where THD is Total Harmonic Distortion
TIF is Telephone Interference Factor

There are strong indications that the 5:th harmonic comes from the network and is not generated by HVDC Light™. Both THD and TIF tended to be rather independent of whether the HVDC Light™ was in operation or not.

Measurements of RI were performed according to ENV50121:1996 at the frequency range 9 kHz – 30 MHz, and CISPR11 at the frequency range 30 MHz – 1 GHz. The measured interference levels were found to be within the specified limits in the whole range except for a peak in the frequency interval 270-300 MHz, where the limits were slightly exceeded in two measuring points.

A staged fault test was made in the 10 kV system at the Garda substation to examine the real effects on the behaviour of the HVDC Light™ link on a three-phase failure in the network. The fault was initiated by closing a 10 kV breaker to a solid three-phase short circuit to earth during 50 ms. During the fault voltage measurements were made in 10 different places. Voltage dips and overvoltage amplitudes defined and evaluated as 20 ms RMS values are given in the diagram below for some of the nodes during one of the short circuits with HVDC Light™ DC voltage of 155 kV. In figure 3 the corresponding values from the SIMPOW simulations for the Garda 10 kV, 50 ms three phase short circuit to ground, are compared with the measurements. The test results showed, that the voltage dips were smaller than at the conditions before the HVDC Light™ installation and the late increase of windpower.

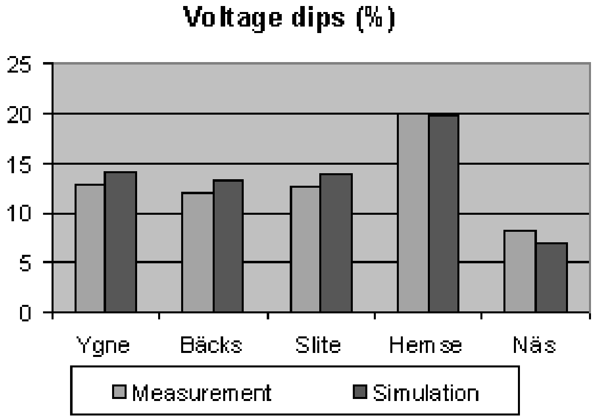

Figure 3.1 Voltage dips.

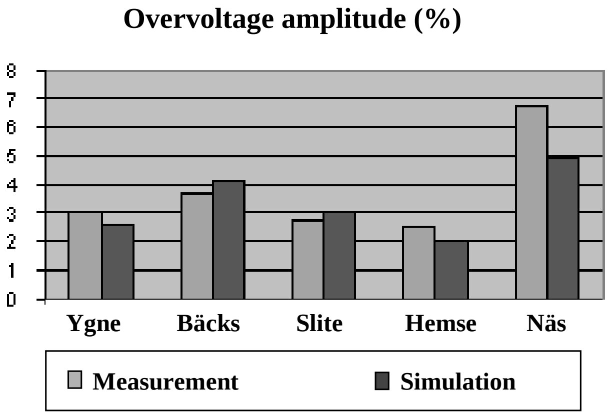

Figure 3.2 Overvoltage amplitudes.

6.2 Tjæreborg

Tests to investigate the behaviour and the co-operation between the HVDC Light™ and the wind farm were carried out on the Tjæreborg HVDC VSC project. Tests performed during commissioning are commented below.

At start/stop of wind turbines changes to transmission power was noticed only as corresponding active power changes without affecting the voltages in the connected networks. This was independent of the level of production at the event.

Start against black network is interesting for example at isolated power plants. When starting the wind farm as a black network the DC feeder was energised from the AC network via Tjæreborg substation, normally operating as inverter. Thus also the converter at Tjæreborg wind farm is energised via the DC network.. At the start it was shown that it is possible to determine both the voltage amplitude and frequency at the wind farm from the converter. The AC voltage can be ramped up smoothly by the VSC and transient overvoltages and inrush currents at energisation are avoided. The wind turbines were automatically connected to the 10 kV bus after seeing the correct AC voltage for 10 minutes. No difference between being solely connected to the HVDC Light™ or to the AC network could be noted.

During isolated operation the Tjæreborg HVDC Light™ connection has been designed to vary the AC voltage frequency between 30 and 65 Hz. With connected wind turbines the frequency was varied between 47 and 51 Hz during commissioning. Outside these frequencies the wind turbines are presently tripped by their abnormal frequency protection. A separate test with disconnected wind turbines was performed. The test demonstrated the capability of the VSC to vary the frequency between 30 and 50 Hz. When lowering the frequency the voltage amplitude is proportionally decreased to maintain the same flux in the generators and thus avoid saturation.

Simulation of three-phase faults in the receiving network of 180 ms and 250 ms were successfully simulated during commissioning by blocking the inverter temporarily. This possibility of the HVDC Light™ converter to isolate the wind turbines from the undervoltage in the receiving AC network, is important in preventing the wind turbines from tripping at network disturbances.

EMC performance of the HVDC Light™ has been verified by measurements against applicable standards. The measured TIF value is 6.2, which is well below the requirement of TIF 50. The harmonic distortion the measured THD value is 2.1 %. All individual harmonics are well below 1 % except the 5th harmonic, which is generated outside the HVDC Light™ link. The recorded flicker value was Pst < 0.23 which is well below the normal limit of 1.0.

6.3 Eagle Pass

During the BTB tie (HVDC Light™ link) commissioning, measurements were made for different phases of operation to verify the performance. Initial energization of the link was made by deblocking the VSC versus the stronger CFE transmission system, establishing a SVC Light mode of operation. The other side of the BTB was then off-line, i.e. disconnected from its line. The sequence involved charging of the DC link and the harmonic filters on the low voltage AC bus. Before the opposite VSC was deblocked, a steady state no load SVC Light condition was established on the CFE side. The complete start-up sequence including also the energization and start of the AEP-CPL side, was performed within 0.5 seconds.

The transient response of the BTB was checked by switching on one of the capacitor banks at the AEP-Eagle Pass substation. In the actual case, the reactive power from the converter was equal to 18 Mvar before capacitor switching. As the capacitor bank was switched on, the converter responded fast reducing its output with 15 Mvar, corresponding to the size of the fixed bank, settling to a new steady state in a few cycles.

The Black Start function was checked against an artificially created small-islanded "network" mainly consisting of the AEPstep-up transformer. Any larger islanded network was not possible to create, as this would have forced a power outage in parts of the city of Eagle Pass. Black Start was then initiated and the AEP-138 kV voltage was ramped from 0 kV to its nominal value at 138kV. The ramping ended without disturbing the CFE side voltages and currents. During operation of the islanded "network", the AEP 138 kV bus was supplied by the BTB at almost no load condition. The only load consisted of the harmonic filters rated totally 6 Mvar. The system was anyhow observed to perform well.

Finally, during a remote fault, the BTB was in operation at zero transfer power. Lightning conditions in a remote area caused a voltage dip in the AEP-CPL network. During stabilization of the voltage in Eagle Pass the BTB current (capacitive) during the fault condition was increased to almost 1 p.u. to support the bus voltage at Eagle Pass.

The Eagle Pass BTB tie has successfully demonstrated an unprecedented capability of providing reliable asynchronous interconnection between the AEPsystem and the Mexican interconnected network, this is relevant considering the difference of short-circuit power at the interconnection points. Furthermore, the use of VSCs with PWM technique has enabled the flexibility in providing independent voltage control, at the two ends of the BTB, and a bi-directional active power transfer between the interconnected power systems.

6.4 Directlink

The action of the Directlink transmission is shown referred to a fault in the NSW AC system during a storm, December 7, 2000. The three systems were in operation, each one with about 50 MW, power direction North. During the fault the transmitted power decreased to around 30 MW per system, as shown in the oscillogram from the Mullumbimby station (AC voltages, phase currents and DC power in one converter). At clearing of the fault temporary blockings of the converters were initiated. This was followed by a normal recovery, with a smooth increase of the power.

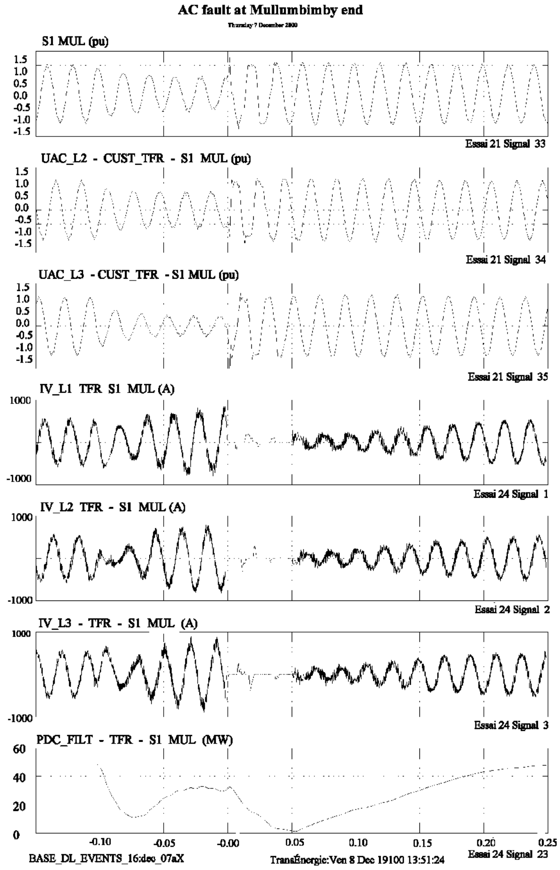

Figure 4 AC network fault on the Mullumbimby side.

It is interesting to see how the Directlink is operated when it comes to active power transmission and referring this to the intentions with the link as undertaken as a generator delivering energy to the highest valued market. The figure below shows how this is exercised in reality. Power is transmitted to the amount and in the direction where it earns money. This shows Directlink as a full commercial player in a deregulated environ-ment directly participating in capacity rights and the spot market. This has been made possible by the HVDC Light™ facility to control in an exact way the flow of energy over the link.

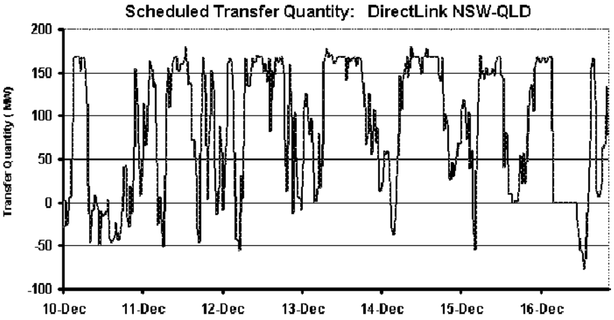

Figure 5 Power transmission by the Directlink.

Initially operating the three links with a weak network (disconnection of lines or shunt banks at one of the stations) showed tendencies to instabilities. This could be counteracted by retuning of the AC Voltage Controls of the links.

7. CONCLUSIONS

Theoretical investigations and simulations have repeatedly shown that HVDC Light™ gives a number of advantages for transmitting power and also for the operation of the surrounding networks. Four HVDC Light™ projects have now been finalized and taken into operation. The experiences from commissioning, trial operation and early operation confirms all expectations Regarding the behavior of an HVDC Light link both with regard to transmission of power and the possibilities to control it. The independent control of reactive power has shown to be very valuable for voltage control and keeping up network operation in connection with disturbances in the network and recovery after disturbances. Features such as black start and variable frequency operation have shown to work well.

8. REFERENCES

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