

THE GOTLAND HVDC LIGHT PROJECT - EXPERIENCES FROM TRIAL AND COMMERCIAL OPERATION

U Axelsson & A Holm

C Liljegren

M Åberg & K Eriksson

O Tollerz

Vattenfall
SWEDEN

GEAB
SWEDEN

ABB Power Systems
SWEDEN

ABB High Voltage Cables
SWEDEN

INTRODUCTION

The electrical system on Gotland, owned by Gotlands Energiverk AB (GEAB) has normally no production except for windpower. The power is provided from the mainland with a peak load of approximately 160 MW, and the frequency is regulated by the HVDC link.

During recent years there has been a large increase of windpower production on the island. In the beginning of 2001 the total installed capacity is 75 MW. In the southern part of the island, where the peak load is about 17 MW, there is about 45 MW windpower installed. The infrastructure built for the existing consumption could not absorb the increased production before the installation of the HVDC Light system. The HVDC Light system made it feasible to use the installed wind power to its full capacity. The windpower production varies at random which means great demands on the voltage regulation.

One important goal for the project is that the power quality for the consumers shall not be lowered after increasing the total installed windpower to 150 MW. HVDC Light was chosen for the transmission of 50 MW to the consumption centers as it was found to be environmentally and technically the best alternative. A DC-transmission parallel to the existing AC network will also contribute to improve the dynamic stability in the whole AC network. Simulations have shown that such a plant will also improve the power quality for the northern part of the island.

The method to use two underground DC cables of opposite polarities lying closely together gives the environmental advantages necessary to obtain a fast right of way permission.

CONTROL FUNCTIONS AND OPERATION EXPERIENCE

HVDC Light control

As an integrated power transmission system, the control of active power in the converter stations should be coordinated. The co-ordination of active power control between the stations is realized by designating one converter controlling the DC side voltage whereas the other converter controls the active power. A constant DC voltage control will result in an automatic balance of active power

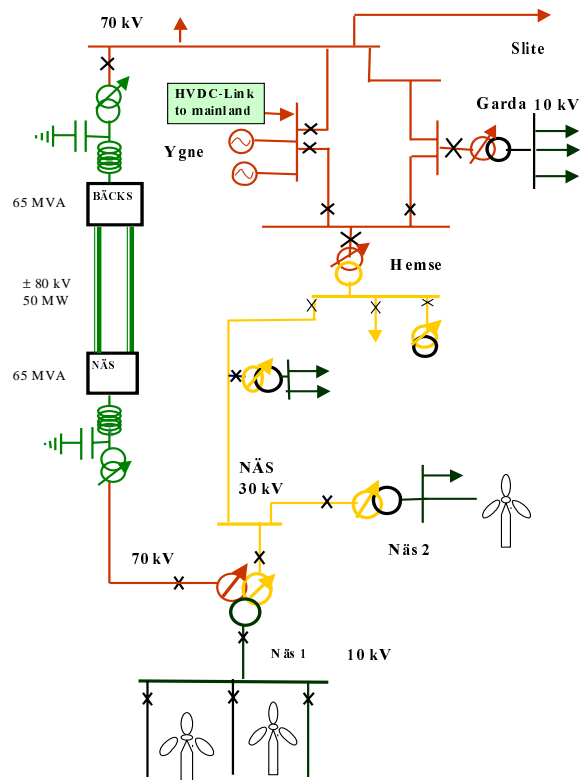


Fig 1. Simplified scheme of the AC network with HVDC Light connection.

flow between the stations. In the Gotland project, the northern station (Bäcks) is normally chosen to control the DC side voltage, whereas the southern converter station (Näs) controls the active power. However, it is possible for each converter station to change from the active power control to the DC voltage control, and vice versa.

The HVDC Light is designed to operate without telecommunication between the two converter stations. Under severe operation conditions such as AC faults in the network close to Bäcks station, the Näs station will automatically adjust the power order setting in such a way that the voltage of the DC link is under its control.

In addition to the active power or DC voltage control, both stations have an AC voltage as well as a flicker control. The AC voltage control keeps the primary side voltage of the transformer to a predetermined set reference value. The flicker control, which works in parallel with the AC voltage control, eliminates voltage fluctuations

mainly caused by the tower shadow effect from the windmills. By using adjustable compounding impedance, it is possible to choose the desired bus, where the voltage fluctuations must be minimized.

Operation of Gotland HVDC Light

In the operating experience of the installation, few faults have been related to the main functions. It has been more common with disturbances related to the recently developed control system, Mach 2, but these disturbances have been solved during the time of operation and there are now few alarms during normal operation. The system work stably, even during faults. During trial operation some phenomena with instability in the network have been observed. These are related to the windpower in very low wind situation, with low generating level, in a weak network.

It has been easy to learn how to operate HVDC Light. The period for tests and measurements has given adequate training how to select the optimum operation mode.

In the Näs application, with very low short circuit power from the network, the voltage is strongly influenced by changes in the power flow, and combined with the asynchronous generation from wind mills, this results in an extreme mode of operation. This should have been difficult for an operator to handle in a conventional AC system. With HVDC Light the risk of overload on the AC line is eliminated as the setpoint for control of active power transmission is on the AC line. The experience has shown that this operation is much simpler than utilising capacitor banks to control reactive power balance on a traditional AC transmission solution.

In order to reduce losses, a function has been introduced, to reduce the DC voltage and make the level dependent on transmitted power. This results in limitations for the utilization of the link, which is being studied further. At a decrease of the AC voltage there is more reactive power margin, than at normal operating mode, see fig 2 below.

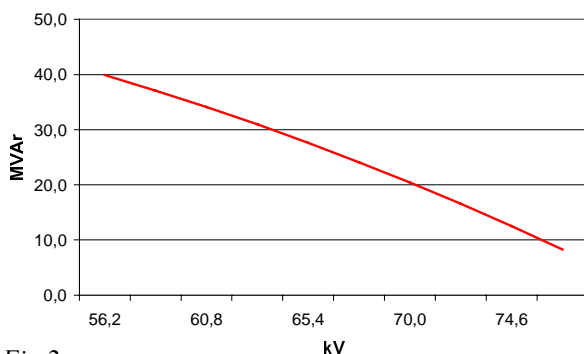


Fig 2. Limitations in reactive power with low DC-voltage (96 kV) for different network voltage.

TEST PROGRAM

Apparatus tests

Most of the equipment in an HVDC Light installation is standard equipment used in conventional AC systems. Some equipment such as the IGBT valves and converter reactors are specially designed for HVDC Light, and no international standards specifying the test procedures are available. For the reactors applicable tests from the standard IEC 60289 "Reactors" were applied to verify the design. For the IGBT valves thorough testing on a full scale phase leg was performed at the STRI (Swedish Transmission Research Institute) research laboratory in Ludvika, Sweden.

HVDC Light cable tests

The HVDC Light cables have gone through an extensive test program including standard type tests, extra type tests, long term tests and after laying tests. The standard type tests were performed according to the same Cigré recommendations as for classic paper insulated HVDC cables, however modified by ABB to reflect voltage properties of HVDC Light Converters. The test results were commendable, and the operation experience of the HVDC Light cable concept in Gotland HVDC Light has been excellent.

System tests

Several tests were made both in the factory and after installation in order to verify the design of Gotland HVDC Light. A few of the most interesting tests are highlighted here.

Factory Tests

The system tests for the Gotland HVDC Light transmission started at the STRI laboratory in Ludvika where one complete converter station was installed and tested during the summer of 1999. This had been preceded by a Factory System Test of the control system. The aim was to verify the mechanical interfaces for the first HVDC Light station of size, and also to test the operation of one full scale station.

Operation modes

After installation and during the three month long trial operation period several system tests were performed in order to verify that the HVDC Light installation functioned according to the technical requirements. The function was analyzed during fault cases and for several regulation mode shifts executed manually or automatically. The tests included ramping of active and reactive power, ac voltage control, reactive power control, flicker control, temporary blocking the valves etc.

An additional operation mode that was tested is the SVC stand-by mode that often is used at low windpower pro-

duction. The converter in Näs is then deblocked operating as an SVC stabilizing the AC system voltage. The Bäckes station is blocked but in stand-by mode, which means that the station is energized. In case of a voltage dip in the ac network, the Bäckes station is deblocked generating reactive power within about 50 ms in order to support the voltage.

MEASUREMENTS IN STEADY OPERATION

During the year of 2000 a very extensive measurement program was executed at the Gotland HVDC Light system. Different measurements of EMC, power quality and audible noise were done at the converter stations, but also in different points in the Gotland network. The program was determined and executed jointly by ABB Power Systems, Vattenfall Utveckling, GEAB and STRI.

Harmonics at the Bäckes station

Harmonics were measured at the 70 kV ac network side in Bäckes. The following values were measured during one week.

THD (%)			THD excl. h5 (%)			TIF			I_{pe} (A)		
1.5			0.6			26			1.5		

where THD is Total Harmonic Distortion
TIF is Telephone Interference Factor
 I_{pe} is psophometric equivalent current

During this time the HVDC Light link was considered to be running under normal conditions. The voltage THD is equal to the recommended limit of 1.5%. Excluding the 5:th harmonic the voltage THD is reduced to 0.6%. 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.

Harmonics at the Näs station

The harmonics in Näs were measured at 70 kV AC network side, 30 kV level and 10 kV level. The following values were measured during one week.

THD (%)			THD excl. h5 (%)			TIF			I_{pe} (A)		
U70	U30	U10	U70	U30	U10	U70	U30	U10	130		
1.3	1.5	1.5	0.9	1.0	1.0	12	42	34	1.0		

The recommended limit for voltage THD for 30 and 10 kV levels is 4.5%, and for 70 kV level 1.5%. The psophometric current, I_{pe} , on the 30 kV line is equal to the limit.

Radio Interference

Well shielded valve enclosures have been used to avoid direct radiation from the fast switching IGBT valves, and the phase reactors have been installed in shielded enclosures. The whole VSC converter has been placed in a shielded building and all connections are made with shielded cables. Conducted disturbances are limited by RI reactors.

Measurements of RI were performed according to ENV50121:1996 in the frequency range 9 kHz – 30 MHz, and CISPR11 in the frequency range 30 MHz – 1 GHz, using peak detection.

The measured interference levels were found to be within the specified limits in the whole range except in the frequency interval 270-300 MHz, where the limits were exceeded slightly in two measuring points, see Fig 3. Quasi peak measurements would have decreased the level somewhat and detailed measurements of the critical frequencies showed that the required level did not exceed more than 3 dB. As the levels are very close to the requirements, it is concluded that this will not cause any problem in the future for the Gotland HVDC Light project. The results from the measurements will however serve as a base for improvements in the station design to lower the interference levels even further.

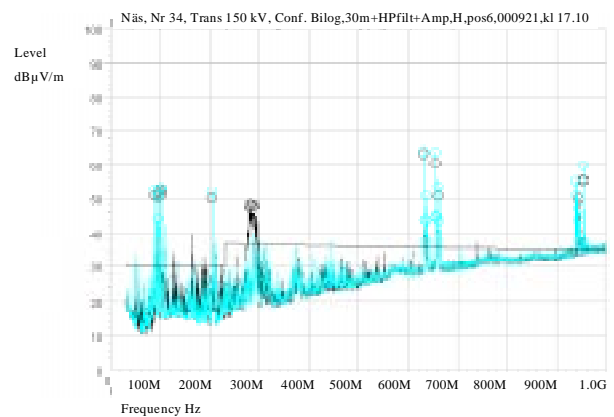


Fig 3. RI measurement in Näs, 30m from the wall of the HVDC Light building. The gray curve is background measurement and the black curve is transmission $U_{dc}=150$ kV.

Losses

The wind power units produces most of the time no power or low power. The recalculated full power utilization time is only 2000 hours per year for land based units and the total running time is around 6000 hours out of the years around 8600 hours.

Due to higher losses in the HVDC Light system than in the parallel AC line an optimization of power flow between the two lines has been made to minimize the overall system losses. In this application it is very important to reduce the HVDC Light losses also in pure SVC mode and for low power transmission.

The DC voltage is the most important parameter for the HVDC Light valve losses. The isolation transformer tap changer makes it possible to vary the DC voltage between 95 and 155 kV. This is utilized with a load dependent DC

voltage function so that the lowest possible DC voltage is used when active power is low.

The loss measurement statistical accuracy has been estimated by STRI to be 4 % for stand-by and SVC cases and 11 % for transmission cases. The ambient temperature during these measurements was in the range of 5-15°C. The given total system losses for the transmission cases are higher than actual operation values due to higher DC voltage during the measurements. The loss sensitivity is around 10 kW/kV(DC).

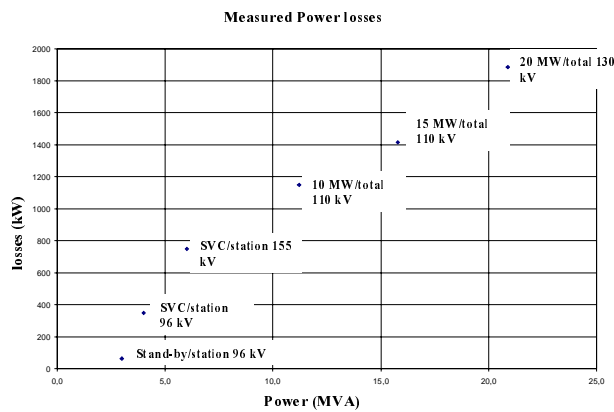


Fig 4. HVDC Light power losses.

Audible noise

Audible noise measurements have been performed at the Bäckes and Näs converter stations. It was then found that the dominating sound sources were the filter capacitors and the filter reactors. The phase reactors did not contribute to the sound power as they are placed far away from the openings in the station building. Measurements made at a distance of 100 m, 200 m and 300 m from the stations showed that the audible noise from the fans in the valve cooling system, even with all the fans running, could not be noticed above the background noise level even if these low frequencies, 60-300 Hz, are poorly damped in air. The critical frequency in the measurements was found to be 1900 Hz, which is close to the switching frequency.

The measured sound pressure L_p was:

- 100 m dB(A) 48.5
- 200 m dB(A) 41.5
- 300 m dB(A) 37

This is below the required 40 dB(A) at a distance of 300 m from the station.

The measurements were made when the stations were running at low power as the wind power production is not fully developed yet. Only a slight increase in the sound pressure at full power is expected, as for the dominating sound sources the harmonic currents will not increase at full power.

GARDA STAGE FAULT TEST

One goal for the project was to be able to provide the same voltage quality to the customers even after a big windpower expansion. To verify this four fault cases were simulated in computer-models with the whole system represented.

In Garda it was possible to verify one of these cases by a solid three-phase short circuit to earth. During the fault voltage measurements were made in 10 different places.

A fault breaker was closed and the ordinary overcurrent protection was used to trip the same breaker. The fault time was not longer than 50 msec, but this was sufficient to show the response from the main system components. The power response was measured from some windmills, the synchronous generators and the main-land HVDC-link, and of course from HVDC-Light.

Voltage dips were measured with a sampling speed of at least 1000 Hz. Voltage dips are defined and evaluated as 20 ms RMS values. The diagram below gives the node names and voltage dips during one of the short circuits with HVDC Light DC-voltage of 155 kV. Another short circuit was performed with HVDC Light DC-voltage 96 kV with similar results.

In Fig 5 the voltage dip values and overvoltage amplitudes from the SIMPOW simulations for the Garda 10 kV, 50 ms three phase short circuit to ground, are compared with measurements for some important grid nodes.

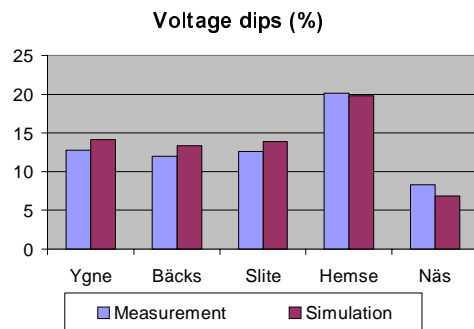


Fig 5 a. Voltage dips.

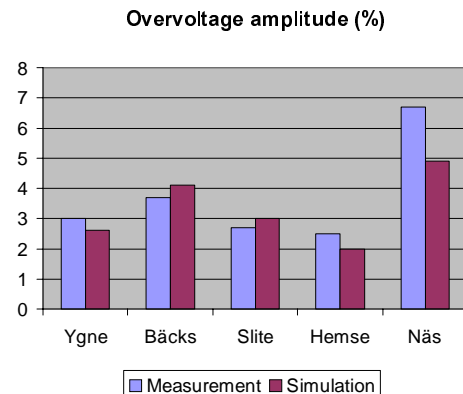


Fig 5 b. Overvoltage amplitudes.

The instantaneous reactive power during the fault from Bäckes was 35 MVar, and from the synchronous generators in Ygne, 30 MVar. HVDC Light is thus the main support for the voltage in the system during the fault.

The test worked well, the voltage dips were smaller than the conditions before the HVDC Light installation and the late increase of windpower. The goal is though to set the HVDC Light gain even higher in order to achieve even better performance.

HVDC LIGHT AND GRID SIMPOW MODEL VALIDATION

The SIMPOW simulation package is designed to give correct results for dynamical events but not for transients.

SIMPOW validation efforts have so far mainly been addressed to adjust the reactive power response from the HVDC Light stations to measured values of voltage dips and overvoltage in Näs and Bäckes. In Fig 6 and 7 two simulation signals, grid 70 kV phase voltage and reactive current, is compared with measurements for the Garda fault in the Näs HVDC Light station 70 kV bus.

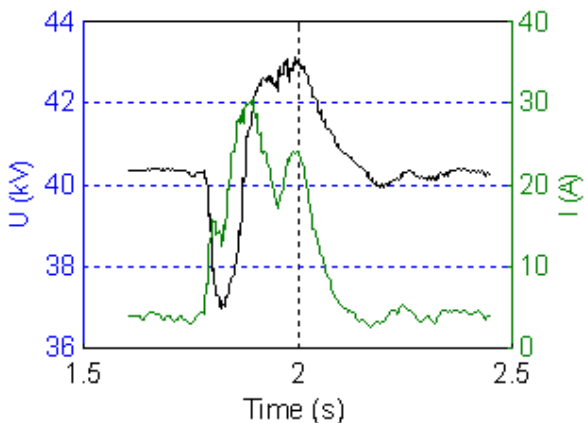


Fig 6. Measurements.

The bar diagrams in Fig 5 shows good agreement between simulations and measurements. It can be seen in Fig 6 that the reactive power response from the HVDC Light stations are not optimized. The delayed maximum values of reactive current after the fault is cleared gives a higher, than expected, overvoltage. In the continued development activities efforts will be made to further improve this performance. The SIMPOW simulation package is designed to give correct results for dynamical events but not for transients.

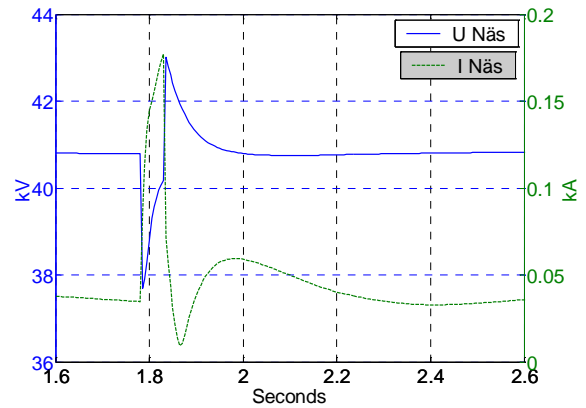


Fig 7. Simulations.

CONCLUSIONS

The HVDC Light installation on Gotland is the first application where a HVDC link is used as an integral part of an AC system. This combined with the environmental demands and the special conditions in the weak network on the Island of Gotland makes this project a very special one that applies high demands on the performance of both hardware and software. The demand for extensive modeling to evaluate the performance and to optimize the control functions has been met by use of the SIMPOW and EMTDC tools. The HVDC Light Cable design has been proven and the environmental advantages have been fully utilized. The controllability has been used for enhancing the power quality and stabilizing the voltage in fault situations, this ability has been proven by measurements and a staged fault test. Both RI and sound levels have been measured and shown to fulfil the stipulated demands. The HVDC Light link has been in operation since November 1999 and is functioning according to expectations. The project has left the building and construction stage. To further exploit the controllability of the VSC converters a follow up project is formed that studies the more sophisticated ways of enhancing performance and interaction with the complex environment of wind power production in the weak network of southern Gotland. §

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