Presented at the CIRED Conference
in Nice, France, May 1999

GOTLAND HVDC LIGHT TRANSMISSION - WORLD'S FIRST COMMERCIAL SMALL SCALE DC TRANSMISSION

by

Urban Axelsson & Anders Holm
Vattenfall
SE-162 87 Vällingby
Sweden
+46 (0)8 739 50 00
urban.axelsson@utveckling.vattenfall.se
anders.holm@utveckling.vattenfall.se

Christer Liljegren
GEAB
Storgatan 95
SE-620 30 Slite
Sweden
+46 (0)498 28 15 00
christer.liljegren@network.vattenfall.se

Kjell Eriksson & Lars Weimers
ABB Power Systems
SE-771 80 Ludvika
Sweden
+46 (0)240 78 20 00
kjell.eriksson@sepow.mail.abb.com
lars.weimers@sepow.mail.abb.com

1. THE GOTLAND HVDC LIGHT TRANSMISSION - THE REQUIREMENTS

The electrical system on Gotland, owned by Gotlands Energiverk AB (GEAB), can be regarded as an island net, although connected by conventional HVDC to the mainland Sweden since 1954. It consists of approximately 300 km of 70 kV lines, 100 km of 30 kV lines and 2,000 km of 10 kV lines. With the exception of wind power, there is normally no production on Gotland. Power is provided from the mainland at a peak load of approximately 170 MW with frequency regulated by the HVDC link. For maintaining voltage stability, synchronous generators also play an important part in system operations. About 900 GWh of energy is provided to 36,000 net customers annually.

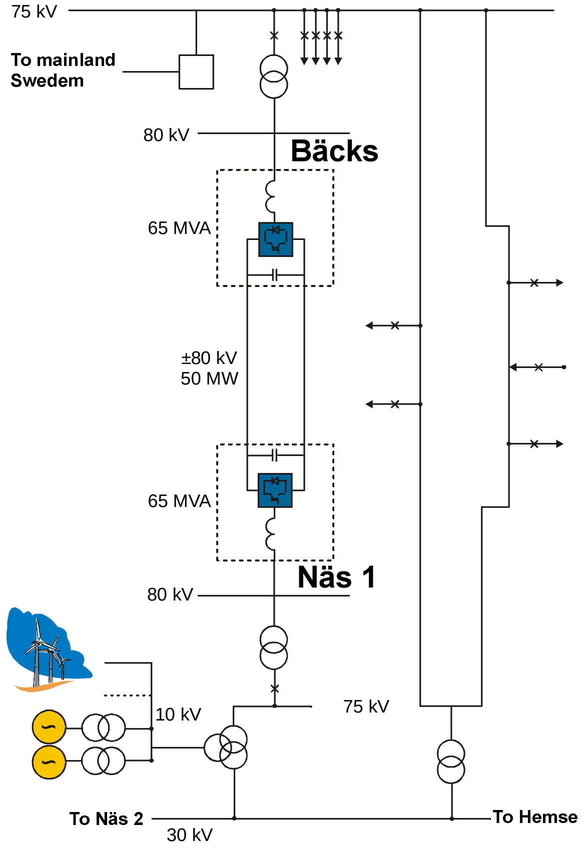

Fig.1. The HVDC Light link incorporated in the Gotland grid.

During the past years, there has been a considerable increase in wind power production. It started in 1984 and reached 15 MW by 1994. Today there are 48 MW installed producing about 100 GWh. On the southern part of the island, where the peak load is only about 17 MW, there is approximately 37 MW of wind power installed. The infrastructure built for existing consumption cannot receive the increasing production. The system is presently used to its limits at full wind power production.

Wind power production does not conform to consumption. The network must be dimensioned to withstand the transmission of production when the load is low, i.e., about 25% of the peak load. The electrical system is built for existing distribution and not for large distributed generation.

Wind power production of this size results in considerable consumption of reactive power, which ought to be compensated in a reasonable way to retain voltage quality while minimizing net losses. Production varies randomly, which puts considerable demands on voltage regulation.

For the successful expansion of wind power, the electrical system must be adjusted so that it can regulate and retain voltage quality in regard to reactive and active power, and other phenomena that arise in an electrical system with wind power production.

2. CHOICE OF TECHNOLOGY

There are two alternatives for transmitting power between Näs and Visby - either AC (cable or overhead line) or DC (cable, HVDC Light technique).

The AC alternative requires, in addition to the transmission lines, equipment for compensation of reactive power, synchronous machines or conventional compensators (SVC), to meet demands for electrical quality. The alternative with synchronous machines would be too expensive (investment, operation and maintenance). Static compensators are untried for this particular application and may not meet demands for electrical quality. An AC three-phase cable is not economically competitive and an AC overhead line would be difficult to build for environmental reasons.

Being the best technical alternative, HVDC Light has been chosen for the project. Power transmission, as well as electrical quality demands on the connecting network, will be met

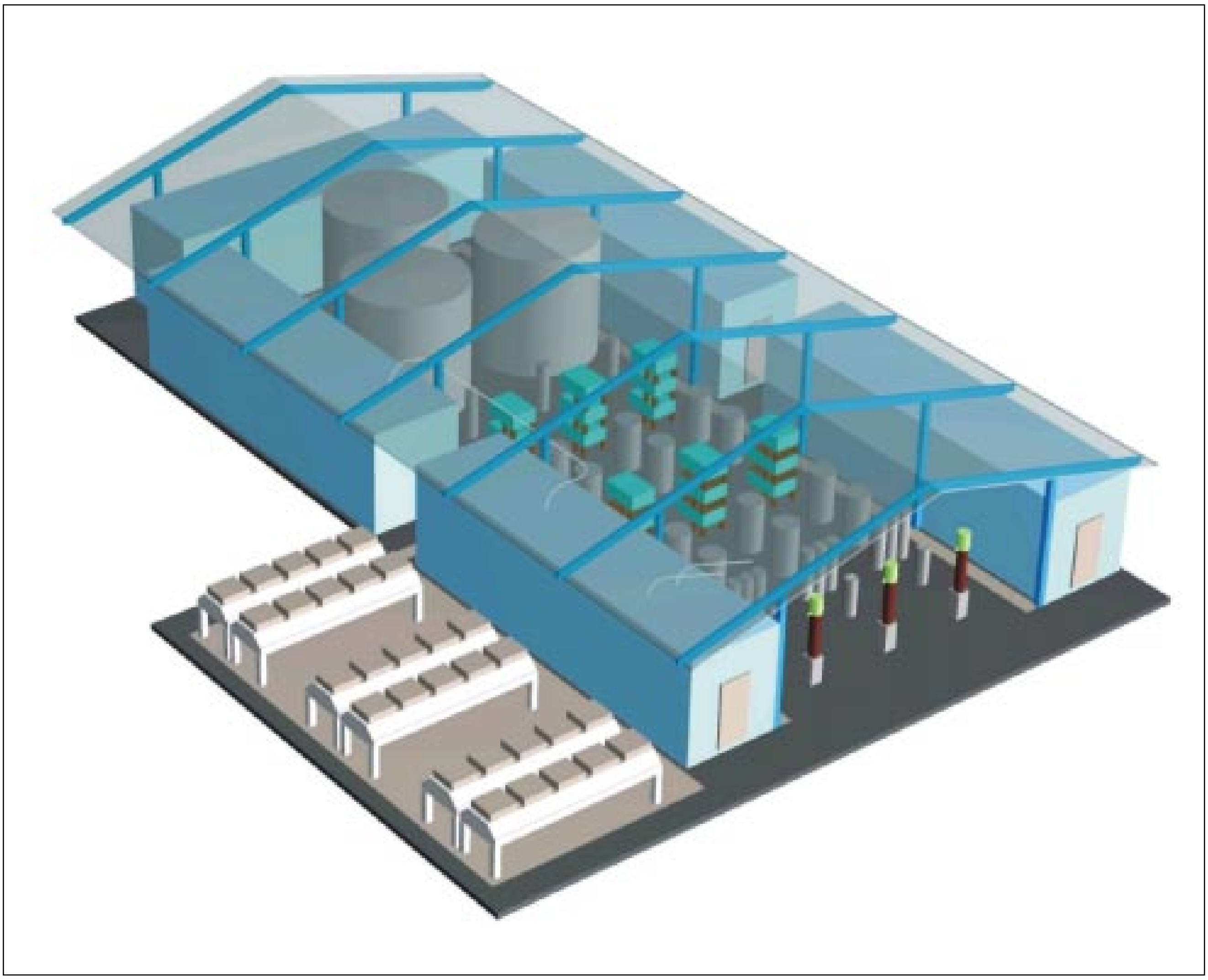

Fig.2. HVDC Light converterstation

with common station equipment. DC transmission parallel with the existing AC network will also contribute to improving the dynamic stability of the entire AC network. Simulation tests have shown that such a plant will also help to maintain electrical quality for the northern part of the island.

2.1 HVDC Light controllability

With HVDC Light, the converter output is determined electronically by control of high frequency, kHz range pulse width modulation (PWM). The control of PWM makes it possible to create any phase angle or amplitude within ratings. Consequently, control signals to a converter can change the output voltage and current from the converter to the AC network almost instantaneously. Operation can then perform in all four quadrants of the power-reactive power plane, i.e., active power transmission in any direction can be combined with generation or consumption of reactive power.

From the system point of view, this corresponds to an electrical machine without inertia that can operate as either a generator or a motor, and by control, be changed between these modes of operation.

The converters can control the transmitted active power so that it corresponds to the generated power from wind power parks and provide the capabilities to follow the rapid changes of power from wind, but also, within certain limits, to even out short dips in power generation. It also makes possible frequency control in one of the networks.

On the Gotland Light installation there will be one DC and one AC transmission line in parallel. If the AC line trips, the production area will become an isolated island. At full windmill production, this means that the windmill generator speeds will increase and eventually trip on high frequency or other voltage criteria (individual windmill protection systems). HVDC Light provides the possibility to control this situation by ordering wind mills to trip and by making a mode shift in the Näs converter from active power regulation to frequency regulation. This could save as much windmill production as the Gotland Light line can transfer.

2.2 Reactive power support and control

Reactive power generation and consumption for an HVDC Light converter can be used for compensating the needs of the connected network within the rating of a converter. Because the rating of the converters is based on maximum currents and voltages, the reactive power capabilities of a converter can be traded for active power capability. The combined active/ reactive power capabilities can most easily be seen in a P-Q diagram. See the following example (positive Q is fed to the AC network).

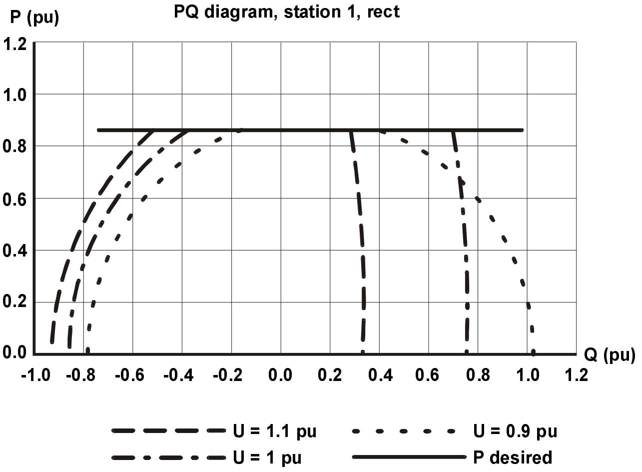

Fig.3. Combined active and reactive power capabilities.

2.3 Voltage control

With the Gotland HVDC Light transmission, the reactive power capabilities are used to control the AC voltages of the networks connected to the converter stations. The voltage control of a station constitutes an outer feedback loop and gives the reactive current order in such a way that the set voltage on the network bus will be retained.

At low or no windmill production, the Bäcks converter shall normally be blocked (in stand-by position) to reduce no-load losses. When a fault occurs that results in a specific AC voltage decrease, the Bäcks converter would have the ability to be rapidly (ms) deblocked and assist with voltage support throughout the duration of the fault, thus avoiding severe disturbances for local industries that are sensitive to voltage dips. The speed of response time for a change in voltage is 50 ms, which means that for a step order change in the bus voltage, it takes 50 ms to reach the new setting. With this speed of response, the AC voltage control will be able to control transients and flicker up to around 3 Hz, as well as other disturbances, and keep the AC bus voltage constant. It is thus capable of relieving a considerable part of the wind power generated flicker from the AC bus.

2.4 Economy

During the evaluation of the project, an alternative with an AC line and an SVC Light compensator at each end of the line was considered. Due to the transmission capacity requirements (50 MW a 70 kV AC OH line was necessary. For the supply of reactive power to the windmills and for stringent power quality requirements it was found that a 20 MVAr SVC Light compensator at each end of the line was needed.

A complication with the AC alternative, and not considered in the evaluation process, was the permit process for an overhead transmission line compared with a buried DC cable. The outcome of an application to build a new AC line was very uncertain and could take much time. For the DC cable alternative, it took only three months to receive all permits.

The total cost for the HVDC Light alternative was estimated to be 115 MSEK, while the cost for the AC alternative was estimated to be 125 MSEK. In addition to the lower investment for HVDC Light, this alternative also offered a significant improvement of the power quality over the entire Gotland AC network and makes it possible to connect additional wind power units in the future. The value of these extras was not taken into consideration in the evaluation.

3. HVDC LIGHT IN THE NETWORK

3.1 Power flow control

On the Gotland network, the introduction of a DC link permits the active power flow in the network to be controlled. The goal, as for reactive power compensation, is to minimize the overall losses in the system and of course, to keep voltage stable. In most cases when production in the south is low, the most favorable alternative is to have the entire power flow through the AC net; for this reason, the no-load losses have to be as low as possible on the DC link. When the need for power transfer increases with increased wind power production, the optimum power flow is calculated in a special module on the SCADA system and a power transfer order is given to the NÄS station that will force the preferred amount of active power through the DC link, resulting in minimized overall losses. The calculation considers both reactive compensation and active power flow; optimization is made for losses in the entire Gotland system. The ability to control both active power transfer and reactive compensation at both ends makes the HVDC Light a very powerful tool for power flow control. The example below shows the figures calculated at a specified amount of wind power production.

Fig.4. Total system losses in AC and DC systems as function av active power transfer in DC system.

3.2 Protection philosophy

Protection for the HVDC Light transmission is installed to remove the equipment from operation in the event of short circuits and other operational abnormalities, especially if they might cause damage to equipment or otherwise interfere with the effective operation of the rest of the system. The protective system is based on the blocking of IGBT valve switching and/or by AC circuit breakers, tripping to de-energize the system and thereby eliminating dangerous currents and voltages. In this protection system, the valves (IGBTs) also play a very important part in stopping the fault current.

AC protection is mainly based on the same standard protection systems used on conventional HVDC projects. Converter and pole protection systems are especially designed for the HVDC Light transmission and are based on the characteristics of the voltage source converter and its active element, the IGBT transistor.

There are specific protection systems for HVDC Light to handle over-currents, short circuits across valves, over-voltages, ground faults on the transmission line, and protection of the IGBT valves. Most of the protection systems block the converter. Blocking means that a turn-off pulse is sent to the valves. They will not conduct until they receive a deblock pulse.

The control system shall, during short circuit faults prevailing for periods of less than one second, aim at avoiding wind power production tripping.

Due to increased wind power production, the grid protection scheme for short circuits must be carefully evaluated. It would be advantageous, as much as possible, that the grid disconnection scheme not be changed and that the flow of fault currents is unchanged. Much is gained if the replacement of protection systems for existing equipment can be avoided.

At low or no-wind power production, the Bäcks converter shall normally be blocked (in a stand-by position) to reduce no-load losses. When a fault occurs that results in a specified AC voltage decrease, the Bäcks converter shall, as quickly as possible (in ms), be deblocked and assist with reactive power support throughout the duration of the fault. Hopefully, this will avoid severe disturbances at local industries that are sensitive to voltage dips.

4 EXPERIENCES FROM CABLE INSTALLATION

4.1 Permits

Applying for permits from authorities (including associated environmental permits) is normally a time consuming process and is often slowed by doubts and questions. With underground DC cables, this process has taken very little time, primarily due to the limited number of questions raised (primarily related to magnetic fields). One hundred and eighty-five property owners accepted within a few weeks. Another contributing factor to rapid approval was that 50 km of the total 70 km run is on the existing 70 kV line right of way. Due to this, lightning over-voltages may have an effect on the insulation of the cable screen. While not considered critical, the phenomenon should be taken into consideration in similar projects.

The method of using two underground cables for opposite polarities lying closely together provides the environmental advantages of a magnetic field of a static nature and reduced to low values.

Fig.6. The Gotland Project HVDC Light Cable. Rated voltage, +/- 80 kV DC. Power required 50 MW. Diameter 44 mm.

Fig.7. Ploughing of cable, normally at a depth of 65 - 70 cm.

4.2 Land use and installation

The cable has been laid with nearly the same method as used for mid-range voltage cables, i.e., plowing the cable down to a depth of at least 65 cm. Work has been planned so that the locations of the joints are convenient (at road crossings, for example). The cable lengths have been adapted to the joint locations at the factory. About 20 km of the 70 km is over rocky terrain. In these areas, a rock-milling machine with a width of 120 mm has been used. The impact on the environment has thereby been kept to a minimum.

What differs from conventional cable laying is the logistics for the 10,000 kg cable drums, each holding approximately 3.5 km of 340 mm^2 cable. The 48 cable drums have been transported with standard trucks to sites. The cable lengths have been laid out on the ground before being plowed down. The best machine for the plowing job proved to be a timber hauler with an added cable drum stand.

When the rock-milling machine had to be used, it was possible to lay 300 meters of cable per day. Daily totals were otherwise several kilometers per day. Dealing with road and watercourse crossings, and moving telephone cables, power cables and the like is time consuming; actual cable laying is not the limiting factor.

It has been possible to lay cable at temperatures as low as -10° C

Fig.8. After ploughing and restoration.

5. VIEWPOINTS ON APPLICATIONS

When an HVDC Light installation is of interest, it can usually be placed in one of the following main application categories.

- *feeding of isolated loads*
  This usually refers to a feeder to a distant location - a town, a mine, to an island or even to a production platform in the sea—that requires power from the mainland.
- *asynchronous grid connection*
  A connection between two networks with different frequencies, different control programs for frequencies or different voltages. It can also be that a sensitive load needs an asynchronous connection to safeguard the power quality of the bus.
- *feed from small generation*
  HVDC Light provides capabilities to transmit power from isolated generation to a grid or to a separate load. Power can be fed in from wind, hydro, tidal, or solar power sources, for example, and configured in any proportion without affecting the power quality of the receiving network.
- *dc grids*
  The technical characteristics that make HVDC Light an excellent component for multi-terminal connections, paralleling and for constructing DC grids.

The decision to use HVDC Light for a specific application is in many cases, based more on characteristics other than those related to costs, and when such supplemental characteristics are considered to be at least as important. For the Gotland transmission, two such characteristics were seen as important:

- the possibility to transmit power over long distances using a completely underground connection—a characteristic that eased the permit application procedure.
- the individual controllability of reactive power for the two stations, providing options for controlling the AC bus volt ages and thus keeping the power quality high.

6. CONCLUSION

HVDC Light is a very valuable transmission vehicle in various situations, as shown by the Gotland HVDC Light:

- for compensating varying load flows due to variations in generation and in assisting in keeping a stable voltage level.
- for optimizing the reactive balances with regard to losses and voltage stability.
- for the easy granting of permits due to the simplicity of cable laying and for keeping environmental impact low, especially when overhead lines are perceived negatively.
- when a short project schedule is of value.