# FEASIBILITY STUDY REGARDING INTEGRATION OF THE LÆSØ SYD 160 MW WIND FARM USING VSC TRANSMISSION

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## ABSTRACT

**The proposed Læsø Syd wind farm along with Eltra's ac transmission system is under study to examine the feasibility of applying the relatively new technology of a voltage sourced converter (VSC) transmission feeder. As an alternative to VSC transmission, an ac feeder is modelled and used for evaluation of ac cables against dc cables. The models are implemented in the simulation program PSCAD/EMTDC with which a comprehensive study under various contingencies and control strategies is being undertaken. VSC transmission technology is described along with practical experiences gained so far from the Tjæreborg HVDC Light project. Preliminary findings are presented in the feasibility study regarding the unique controllability of Voltage Sourced Converters and how this features can be applied to the optimal operation of the wind farm compared with ac transmission.**

**Keywords: Demonstration projects, feasibility studies, off-shore**.

## 1. INTRODUCTION

Eltra has as the TSO (Transmission System Operator) the responsibility for integration of two 160 MW offshore wind farms in the Danish territorial waters into the transmission grid in western Denmark. The first offshore wind farm at Horns Rev in the North Sea is situated at a distance of approximately 20-km from the coastline. The total distance to the grid is approximately 35 km. The Horns Rev project is expected to go into operation in 2002. For this site it has been decided to use a 150 kV ac cable transmission feeder.

The second offshore wind farm at Læsø Syd that is situated in the water between Denmark and Sweden south of the island Læsø is planned to go into operation in 2004. The distance from this site to the coastline is 40 - 50 km and the total cable distance to the transmission grid is approximately 70 km. Because of the great distance to the grid, dc transmission with Voltage Source Converters could be a feasible solution compared with ac cables. Ac cables inherently generate reactive power that sets a limit for the maximum permissible ac cable length. This is known as the critical ac cable length.

Dc transmission with Voltage Sourced Converters (also called VSC Transmission) is a rather new technology which became available recently when ABB launched their new concept called HVDC Light [1]. In order to test and demonstrate the suitability of VSC transmission [2] for the Læsø offshore site, Eltra decided to test the new technology at an onshore location and for this purpose the Tjæreborg VSC Transmission project was initiated and built. This project collects electric wind energy from a small wind farm and transmits it through a 4 km dc cable to a 60/10 kV substation where it is converted back to ac and fed into the grid. From this project Eltra expect to gain valuable experience and confidence in the new technology.

In addition to the practical experience gained from the Tjæreborg VSC Transmission project, Eltra also found it necessary to undertake a feasibility study in order to investigate the application a VSC Transmission feeder for Læsø Syd 160 MW wind farm.

## 2. VSC TRANSMISSION

### 2.1 Description of VSC Transmission

A VSC is a three-phased AC/DC converter based on electronic valves that can be switched on and off (GTO, IGBT, IGCT…) and controlled by PWM (Pulse Width Modulation). This makes a VSC behave as an autonomous ac voltage source, the amplitude and phase of which are controlled, up to some limits.

A VSC is connected to the ac grid through a reactor that transforms the difference of amplitude between grid voltage and converter voltages into a reactive current. Additionally, if the two voltages present a phase difference, an active component appears in this current and active power is exchanged between the ac and dc sides of the converter.

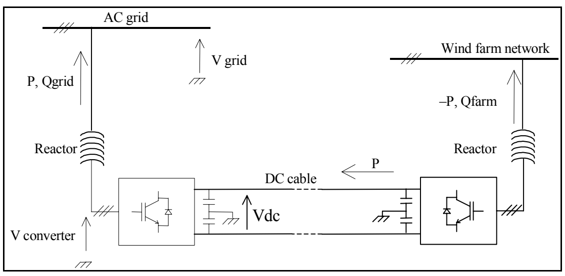


**Figure 1:** Principle of a VSC Transmission scheme

A VSC Transmission scheme consists of two VSC connected each to an ac network with the dc sides linked through a dc cable. Each VSC is able to exchange reactive power independently with the ac network it is connected to. The dc link allows exchange of active power between the two ac networks. The principle of a VSC Transmission is presented in figure 1.

### 2.2 Limits

As for most of the power electronic devices, VSC rating is limited by the current capability through its switches (or valves as they are sometimes known). Since this current is an image of the ac current that is both active and reactive, the operational limit of a VSC, seen from its ac side, is its nominal apparent power Sn. Thus, the active and reactive powers (respectively P and Q) delivered to the grid by the VSC are limited to the operational domain described in figure 2.

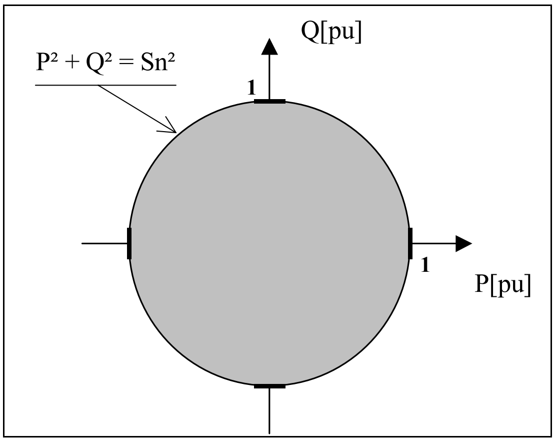


Figure 2: Operational P and Q limits of a VSC

### 2.3 Characteristics of VSC Transmission

Compared to an ac connection, VSC Transmission gives a large number of degrees of freedom at both ends. When connecting a wind farm to the grid, VSC Transmission provides the following advantages:

- Grid voltage control: Thanks to reactive power exchange possibilities, the VSC connected to the grid allows control of ac voltage at its connection point. Within operational limits, this voltage control is possible independent of the active power flow level.
- Weak network supply: Since a VSC is an autonomous AC voltage source, the VSC at the network side does not need a high short-circuit power nor rotating machines to operate, the VSC Transmission may supply weak networks or even passive loads.
- Frequency control: Since a VSC is an autonomous AC voltage source, the VSC located at the wind farm side provides a frequency control. The wind farm ac frequency may be adapted for the generators to reach their optimally efficient operation point according to the measured wind velocity.
- Reference voltage: Since a VSC is an autonomous AC voltage source, the VSC located at the wind farm side provides the ac voltage mandatory to operate induction generators. Thus, the use of a VSC makes it possible to generate power with simple and robust squirrel caged induction generators.
- Wind generators reactive compensation: In the case of the use of simple induction generators, each machine is equipped with its no-load condensers. When loaded, the rest of the reactive power needed by the generators is provided by the VSC located at the wind farm side.
- No critical length: A VSC Transmission cable may be as long as needed, it does not suffer from the ac critical length due to reactive power compensation.
- Energy storage: The dc bus might be equipped with an energy storage device to provide functions such as generation levelling, primary reserve, black-start…
- Flexibility: The power exchange between the wind farm and the grid may be controlled precisely by the means of the VSC Transmission. For example, the VSC Transmission start and stop may be progressive in order not to disturb the network with steep power transients.

A VSC Transmission has also the following drawbacks compared to ac transmission:

- Cost: Since VSC Transmission is a young concept, its cost is quite higher than the equivalent ac link.
- Losses: The high frequency PWM switching leads to large losses, compared to these of an equivalent ac link. These losses may prevent the use of wind generation under a minimal generated power (i. e. a minimal wind velocity).

## 3. TJÆREBORG VSC TRANSMISSION PROJECT

The purpose of the Tjaereborg project is to investigate the use of the new HVDC concept using VSC as transmission feeder for wind farms and in particular offshore wind farms where long submarine cables were required. Ac cables inherently generate reactive power setting the limits of how long an ac cable can be without compensation with shunt reactors. Dc cables do not generate reactive power and there are therefore no technical limits of the distance length.

Application of classical HVDC transmission has been used for many years to interconnect non-synchronous ac power systems. Classic HVDC is, however, not practical when connecting wind power, because this technology uses phase controlled converters (PCC) where the converters are only operational if connected to an energised ac grid with a certain short circuit level. In addition to this, phase differences are always present between ac voltage and ac current in the PCC even though it is operated as rectifier or inverter. This converter type therefore always consumes reactive power, which is about 50% of the transmitted power.

The wind farm in Tjaereborg consists of the following four wind turbines:

1. 1.0 MW Bonus wind turbine with active stall and a frequency converter in the main circuit
2. 1.5 MW NEG Micon wind turbine with stall regulation and induction generator
3. 2.0 MW Vestas wind turbine with a frequency converter in the rotor circuit of the induction generator (a double-feed induction generator)
4. 2 MW test turbine with stall regulation and induction generator

During the HVDC project both the Bonus and the Vestas wind turbines were rebuilt with converters and the Vestas wind turbine was upgraded from a 1.5 MW to 2.0 MW induction generator. In addition to this, the 2 MW test turbine had a break-down due to a fault in the wind turbine control system during commissioning of the HVDC link so the total installed capacity of the wind farm is now 4.5 MW instead of 6.5 MW and the HVDC connection can therefore not be tested at full load.

The wind turbines are connected via two 4 km ac cables to a 60/10 kV substation. The HVDC low power converter station at the sending network is established at the wind farm, whereas the converter station at the receiving network is placed at Tjaereborg 60/10 kV substation. The two dc cables shown in Figure 1 are parallel with the existing ac cables. With this configuration it is possible to operate the wind farm via the old ac cables or via the dc cable or with the ac and the dc cable in parallel. Due to this it was decided to implement a control function for automatic switching between the ac and the dc cable connection. Because the losses in the converter stations are rather high due to high switching frequency (1,950 Hz) the wind farms are operated via the ac cables at a wind power output below 500 kW and it automatically switches to the dc cable – isolated operation mode – when the wind power output is higher than 750 kW for more than 10 minutes. Operation with the ac and dc cable in parallel is only used during commissioning and for test purposes.

Technical Data for the Tjæreborg VSC Transmission:

| | |
|---|---|
| Converter type | 2 Level VSC |
| Valves | Series Connected IGBT |
| Cooling system | Water |
| Rated power | 8 MVA/.,2 MW |
| Switching frequency | 1,950 Hz PWM |
| D.c. voltage | +/- 9 kV |
| D.c. current | 358 A |
| D.c. cable length | 2 x 4.3 km |
| A.c. grid voltage | 10.5 kV |

The dc side is provided with a dc zero sequence transformer (common mode blocker) and in addition, two 120 mm2 CU lines are laid close to and in parallel with the DC cables for screening.

Telephone interference level is better than 50.

### 3.1 Steady State Control

The power transmission from the windmills to the ac network can be done in three different operating modes, ac feeder only, dc feeder only or ac and dc feeder in parallel. Tjæreborg HVDC project (HVDC Light) has the feature that it can automatically switch between these operation modes. The reason is to minimise the losses at low power. In other applications, isolation from a parallel ac network can also be of interest, such as a radial interconnection of wind farms.

In normal operation the VSC situated in the isolated wind farm absorbs the active power that is produced by the windmills and sends it through the dc cables to the VSC situated in the receiving network. The dc voltage is controlled by the receiving VSC by injecting the received dc power into the ac network.

The reactive power in each station is controlled independently of the other station. In the isolated wind farm the reactive power is regulated to maintain the ac voltage at the selected reference level, since the induction generators have no inherent voltage controlling capability. On the ac network side the reactive power is controlled to a selectable reference.

### 3.2 Variable frequency

In isolated operation the Tjæreborg VSC Transmission has been designed to be able to vary the ac voltage frequency between 30 and 65Hz. This ability to change the stator frequency of the induction generator makes it possible to optimise the power output from the wind turbine by adjusting the frequency in relation to the wind velocity. With windmills connected, the frequency was varied between 47 and 51 Hz during commissioning. Outside these frequencies the windmills are presently tripped by their abnormal frequency protection. A separate test with the windmills disconnected 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 decreased proportionally to maintain the same flux in the generators and thereby avoid saturation.

### 3.3 Dynamic Properties

By use of a dc link the wind farm is isolated from the ac network, which gives the advantage that the voltage in the wind farm is not affected by changes of the voltage in the ac network, caused by switching actions or remote faults. For faults in the ac network with low remaining voltage the active power cannot be injected into the ac network. The produced power in the windmills can then be stored temporarily in the windmills by letting the rotor speed increase. When the fault in the ac network is cleared the excess energy in the windmills can be injected into the ac network and the pre-fault rotor speed is resumed. A fault with duration of 250 ms gives a frequency increase of approximately 1.9 Hz at full wind power generation. When the generation is lower it will take longer time to reach the same amount of over speed. If the ac network does not recover until the overspeed limit is reached the windmills are tripped.

### 3.4 Handling of faults and disturbances

In order to protect the equipment, the converter stations are divided into protection zones where the currents and voltages are measured. If abnormal currents or voltages are detected due to a fault within the station, the converter valves permanently block and the ac breaker is tripped and locked out. With an underfrequency or overfrequency of the ac network the converter is also blocked and the ac breaker is tripped.

Faults in the ac network can sometimes give a fast increase of the converter current. In order to protect the valve, a short temporary block of less than one period is used, after which the valve is deblocked again to resume power transfer.

The windmills are safeguarded by their own protections. No specific protection solution is needed for co-operation with the HVDC Light. The most important safeguards from the system point of view are; overspeed, underspeed, overvoltage and undervoltage protections. In addition there are protections against motor operation of the windmills.

When the windmills trip, the HVDC Light will continue to operate, with the Enge rectifier working as a stiff voltage source, allowing normal restart of the windmills. Of course, no active power is transmitted. When the Enge rectifier trips, the converter is blocked and the ac breaker is tripped. The ac voltage will immediately drop to zero, and the windmills are tripped by the undervoltage protection with the overspeed protection as a back up.

When the inverter in the Tjæreborg Substation trips, the Enge rectifier will continue to keep the ac voltage at the reference value. However, as the power transmission is stopped, the frequency will increase. Either the Enge rectifier is tripped due to overfrequency, resulting in the above described undervoltage trip of the windmills, or the windmills are tripped by their overspeed protection, depending of the operation conditions.

### 3.5 Commissioning experiences

Coordinating the operation of VSC Transmission with the wind farm was investigated prior to commissioning, mainly with PSCAD. During commissioning relevant tests were repeated. To minimise the system disturbances during commissioning some disturbances were simulated. Among the various tests that were performed to investigate the behaviour and to prove the function of the Tjæreborg VSC Transmission project, the most interesting tests were:

- Start/stop of wind turbines at low and high wind velocities.
- Switching between the different operation modes with the ac and dc feeders.
- Start against black network.
- Varying the frequency in the wind farm (described above).
- Verification of protections.
- Simulation of three-phase faults.
- EMC measurements.

### 3.6 Start/stop of wind turbines

Start of wind turbines was only noticed as a slow increase in power, as the windmills are equipped with smooth starters. Stop of wind turbines is equal to a step decrease of active power. In isolated (dc) mode the VSC absorbs the active power at the frequency selected by the operator. The ac voltage is kept at the reference value by regulating the reactive power in the wind farm. The reactive power generation in the receiving end was not affected by the active power change.

### 3.7 Switching between the different operation modes with the ac and dc feeders

During low generation of wind power the power transmission is performed via the 10 kV ac cable connection, and at wind power generation above 0.7 MW the transmission is performed via the dc transmission. The transition between the ac and dc transmission is performed (as described above) completely automatic without any problem.

### 3.8 Start against black network

One feature with HVDC Light is that it can start up against and feed a black network. This is especially interesting for isolated power plants. When starting the wind farm as a black net the dc feeder is energised from Tjæreborg Substation, thus also the converter at Tjæreborg Enge is energised on the dc side. Deblocking Tjæreborg Enge gives the possibility to determine both the voltage amplitude and frequency at the wind farm. The ac voltage can be smoothly ramped up by the VSC thereby preventing transient over-voltages and inrush currents at energisation. The windmills are automatically connected to the 10kV bus after seeing the correct ac voltage for 10 minutes. From their point of view there is no difference between being solely connected to the HVDC Light and to the ac network.

### 3.9 Verification of protection

A number of different protections are implemented to assure the safe operation of the VSC. The main part of the protections acts by tripping the station, i.e. block the converter and open the ac breaker. As the VSC stations can act without communication with each other, the stations are self-protecting. During factory system tests and commissioning the function of all protections was tested.

### 3.10 Simulation of three-phase faults

At fault in the receiving ac network, the power transmission is temporarily stopped until the fault is cleared. This leads to a somewhat increased frequency in windmill network. However, the HVDC Light transmission isolates the windmills from the undervoltage in the receiving ac system, so the windmills see no undervoltage. Ac faults of 180 ms and 250 ms were successfully simulated during the commissioning by temporarily blocking the inverter.

### 3.11 EMC verification

The EMC-performance of the VSC converters has been verified by measurements. Both RI emission and voltage distortion performance has been verified. Regarding RI emission it has been verified that the VSC converter station comply with standard EN 50011 in the frequency range 30 MHz to 1 GHz. In the frequency range 9 kHz to 30 MHz it has been verified that the converter stations comply with section 50121-5. These two standards have been considered as being the most relevant ones for the HVDC Light converter stations. Regarding immunity, the control equipment has been verified against applicable standards as factory type testing.

The measured TIF-value is 6.2 (99% value), which is well below the requirement of TIF 50. The fact that the

HVDC light converters are connected to a 10 kV cable network, combined with the high switching frequency and adequate filtering explain the low values. Regarding harmonic distortion, the measured THD-value is 2.1% (99% value). Highest measured individual distortion was 2.1% (95% value) for the fifth harmonic. All these values are within the stipulated limit for the contribution from the 10 kV system. The recorded flicker value was Pst < 0.23 (95% value), well below the normal limit of 1.0.

## 4. SYSTEM MODEL

The reasons for modelling and studying VSC Transmission connecting the Læsø Syd wind farm to the main electricity grid are to firstly, ensure the undersea and underground cables will be protected against overvoltages. Secondly, to ensure that the wind turbines are able to remain in service during ac system faults and operate at highest efficiency and reliability, and thirdly, to guarantee that there is minimal adverse impact from the operation of the wind turbines on the receiving end ac network.

VSC Transmission allows control of ac voltage and frequency of the ac collector system of the wind farm. Stall regulated turbines can be used with induction generators in speed control achieved through ac frequency control. At the receiving end terminal substation, the VSC Transmission provides strong ac voltage support as it delivers the power from the wind farm to the power system network.

In the simulation model, the frequency of the wind farm ac collector system is controlled directly in proportion to measured average wind velocity and ac voltage is controlled inversely proportional to frequency. A typical range of operating frequency for the wind turbines is between 30 and 52 Hz. In this model, rated power for the turbines is achieved at an optimal wind velocity of 10 m/sec, coinciding with rated rotational velocity of the wind turbine equivalent to 50 Hz. The set point for the frequency order ($F_{order}$) of the ac sending end collector system is:

$$F_{order} = \text{Average wind velocity} \times 5 \Big/_{30\ \text{Hz}}^{52\ \text{Hz}}$$

If the average wind velocity falls below 5 metre/sec or exceeds 25 metre/ sec, the wind turbine protection acts to remove each from service. The VSC Transmission with detailed pulse width modulated converters and controls, the stall regulated wind turbines and wind model as well as an extended model of the Eltra receiving end transmission network is being studied using the PSCAD power system simulation software.

## 5. FEASIBILITY STUDY

The simulation study provides a technical assessment of the feasibility of applying VSC Transmission as a feeder from the wind farm. One of the significant results is observed for an extended single phase ac system fault in the receiving end ac transmission network near the termination point of the VSC Transmission. Here in Figure 3, the ac voltages on phase R of both the receiving end ac system bus near the location of the fault and on the ac collector system of the wind farm are shown. Note how the ac voltage at the wind farm is impacted but not severely. This is significant in that the wind turbine protection system may not operate, and the wind turbines can remain on line.

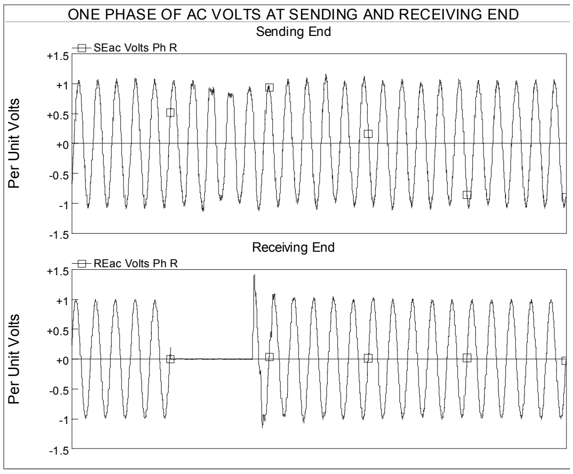


Figure 3: Transfer of an ac fault through a VSC Transmission feeder to a wind farm.

## 6. CONCLUSIONS

The efforts to date by Eltra have demonstrated that VSC Transmission is indeed technically feasible for a feeder from an off-shore wind farm. The installation and operation of the demonstration VSC Transmission system at Tjaereborg has played a significant role in developing confidence and knowledge in this new technology.

Simulation methods have advanced to provide system design capability for integration of the wind farm in-feed into the electric power system. As progress is made towards the development of the Læsø Syd off-shore wind farm site, the selection of either ac or dc transmission will be examined in detail, both technically and economically.

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