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HVDC Light for connection of wind farms

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SUMMARY

In 1998, Eltra, the Independent System operator and the Transmission company in western Denmark decided to investigate the use of the new HVDC Light technology for DC connection of wind power to Eltra´s transmission grid.

There is an increasing amount of wind farms that need to be connected to the AC transmission network. Offshore wind farms will be connected to the ac system via long submarine cables. Integration of offshore wind farms with HVDC transmission based on Voltage Source Converters (VSC), such as HVDC Light, is an advantage due to regulating properties of HVDC Light. The purpose with the Tjæreborg project was to demonstrate on a small scale the application of this new technology for connection of large-scale offshore wind farms. The project was realized on the existing wind farm at Tjæreborg close to Esbjerg on the west coast of Denmark. It was released and started in March 1999 and was taken over for tests and demonstration in December 2000.

VSC with Pulse Width Modulation (PWM) can operate in all four quadrants of the PQ-plane, i.e. it can operate as rectifier or inverter at variable frequency and at the same time absorb or supply reactive power to the AC network. HVDC Light is suitable for connection of wind farms with induction generators, since the wind generators are decoupled from the AC network. In the wind farm, the HVDC Light can supply an AC voltage to a dead net at start up as well as collect the wind power and at the same time supply reactive power to the wind generators. It can also vary the frequency, getting the highest power economy from the wind farm. At the receiving end, the VSC delivers wind power to the AC network and independently regulates the AC network voltage.

The co-operation between the HVDC Light and the windmills was tested by simulations prior to commissioning, mainly in EMTDC. During commissioning relevant test were repeated as applicable. Some disturbances were simulated, for minimizing system disturbances during commissioning. It may be mentioned that black start of the windmill as subsystem from the HVDC Light has been successfully demonstrated. The experience from both commissioning and operation so far shows that HVDC Light transmission based on VSC techniques is a promising concept for connecting large wind farms to ac systems.

With the used concept of the HVDC rectifier working in the stiff voltage mode, the windmills just see the HVDC Light rectifier as a stiff ac network, as they are used to. Thus the introduction of HVDC Light does not introduce any new requirement on the windmills. However, at design of the windmills in the future, the dynamic speed increase at ac system faults must be considered. The reason is that the windmills will in the future not be allowed to trip at temporary ac system faults.

1. INTRODUCTION

The paper describes testing and commissioning of an 8 MVA HVDC Light transmission link with Voltage Source Converters (VSC) for connection of the onshore wind farm at Tjæreborg in the western part of Denmark. The transmission is a demonstration project for verification that DC transmission from a wind farm works properly before applying the concept for larger offshore wind power project. A specific advantage is that the VSC converters can operate in all four P/Q quadrants and thus controlling both the frequency and the voltage at the wind power connection. Furthermore, the HVDC Light transmission is an asynchronous link, which can isolate the power system from the wind power fluctuations, especially because the inverter can also give Mvar support to the receiving ac system. All these facilities have been tested both in simulation and in the real system during commissioning. The experience is that the HVDC Light concept has worked according to expectation. A general description of the project is given in [1].

Prior to delivery, the control concept was tested by EMTDC simulation of various disturbances and fault. No ac side staged fault testing has been performed during commissioning. However, 180 ms and 250 ms faults in the receiving ac system have been simulated for verifying the dynamics of the HVDC Light and the windmills. Other event such as mode shift and switching events have been tested during commissioning and compared with simulation results. In general the agreement between simulation and commissioning test results is fairly good.

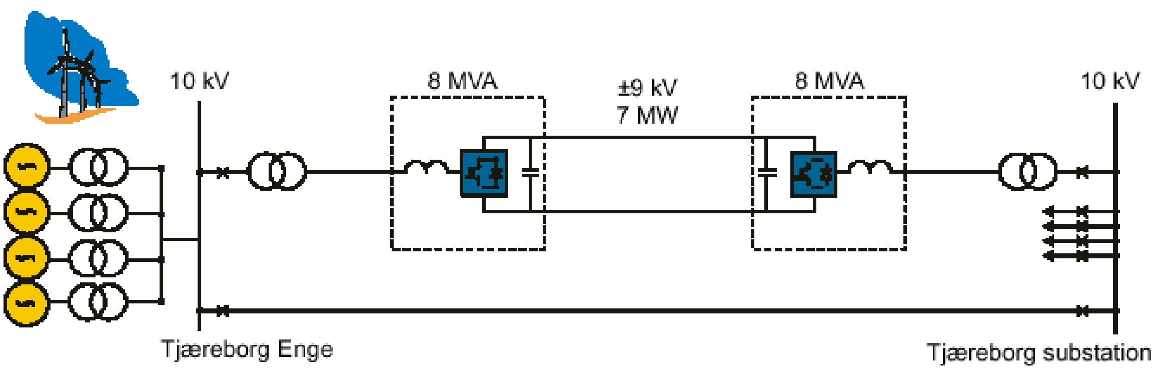
An exception is the frequency control. In the simulation a dynamic frequency control worked fine. However, in reality a concept with the VSC rectifier operation as a stiff voltage source proved to be much more robust and simple. Still it is possible to select the most optimal frequency regarding wind power production. One reason for the deviation between simulations and commissioning results may be due to difficulties in correctly simulating the dynamics of the windmills. With the stiff voltage concept the interaction between the HVDC Light and the windmills is much more robust and simple.

Other aspect have also been verified during commissioning.

2. TJÆREBORG HVDC LIGHT PROJECT

The wind farm in Tjaereborg Enge can be connected to the a.c. network (Tjæreborg 10/60kV substation) either via the HVDC Light or via a 4 km long, 10 kV a.c. cable. The a.c. network is relatively strong at the connection point, 132 MVA.

Figure 1



As HVDC Light d.c. cable was laid in parallel with the a.c. cable, this made it possible to operate the wind farm in three different operation modes. AC mode via the a.c.-cable only, d.c. mode via the d.c.-cable only and parallel mode via the a.c. and d.c.-cables in parallel. Operation of the wind farm in these three different modes makes the demonstration project suitable for an investigation and a comparison of the various operation modes.

The control modes are further described below.

2.1 The wind farm

The Tjæreborg wind farm consists of wind turbines of different types and makes. The NEG-Micron 1.5 MW-mill and Bonus 1 MW-mill are stall regulated and Vestas 2 MW-mill is pitch regulated. A frequency converter between the generator and the step up transformer feeds Vestas' rotor circuit while Bonus is equipped with a frequency converter on the stator.

2.2 Tjæreborg HVDC Light

The HVDC Light transmission, with a rating of 7.2MW, 8MVA, consists of two Voltage Source Converters (VSC) and two ±9 kV d.c. cables.

The VSC converters operates with Pulse Width Modulation PWM technique, as described below, and the nominal commutation frequency is 1950 Hz. The active components in the valves are IGBTs. The converters are connected to the ac system via transformer with dry insulation. Filters are provided for filtering on the ac and dc side

As the stations are placed in an open rural area, all the VSC equipment such as transformers, filters, valves, control and cooling equipment etc are placed in 16 * 22 meter buildings. The exterior of the building resembles a farm house.

To minimize the RI emission from the fast commutation transients the building and the converter equipment is well screened.

3. OPERATION CHARACTERISTICS OF HVDC LIGHT

3.1 Steady State Operation

In a VSC, the current in the valves can be switched on and off at any time—the converter is self-commutated—so that it can feed a passive network. Using high switching frequency components such as IGBTs, it becomes advantageous to use Pulse Width Modulation (PWM) technology. Switching very fast between two fixed voltages creates the AC voltage. The desired fundamental frequency voltage is created through low pass filtering of the high frequency pulse modulated voltage. See Figure 2 and Figure 3.

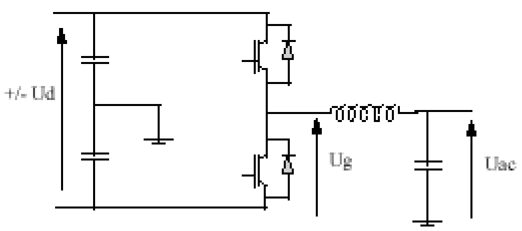


Figure 2 One phase of a VSC using PWM

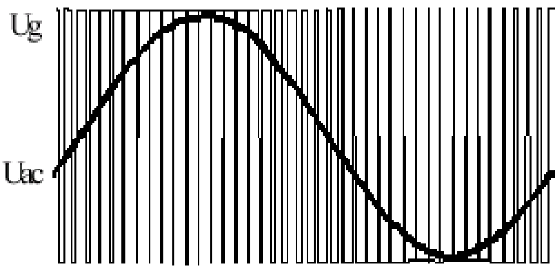


Figure 3 The PWM pattern and the fundamental frequency voltage in a Voltage Source Converter

With PWM, it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. PWM thus offers the possibility to control both active and reactive power independently. The reactive power can be used for compensating the needs of the connected network within the rating of a converter and can be traded against the active power capability. The combined active /reactive power capabilities are depicted in the P-Q diagram in Figure 4 (positive Q is fed to the AC network).

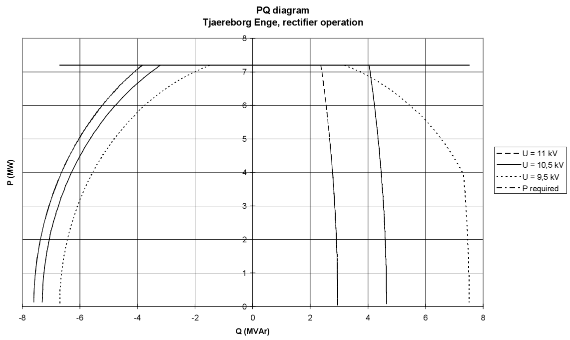


Figure 4. The P/Q characteristics of the HVDC Light converter at the wind farm

The VSC situated in the isolated windfarm absorbs the active power that is produced by the wind mills 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.

3.2 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 can not 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.

3.3 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 blocks permanently and the ac breaker is tripped and locked out. At 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 safeguard 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 is 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.

Figure 5 to Figure 8 shows a temporary block in the station at the receiving ac network with a duration of 180 ms, which was performed during the commissioning of the dc transmission. This was made to simulate a 3-phase fault in the receiving ac network. The wind power is rejected during the fault and when the fault is cleared the dc power is increased in order to deaccelerate the windmills back to nominal speed. This is shown Figure 5 to Figure 7. It can be seen in figure Figure 8 that the voltage in the wind farm is kept close to nominal through the whole fault duration.

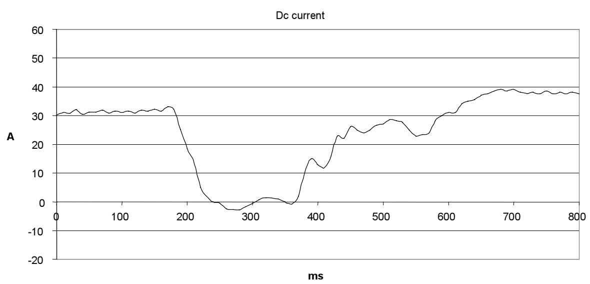


Figure 5 DC current at 180 ms temporary block of inverter.

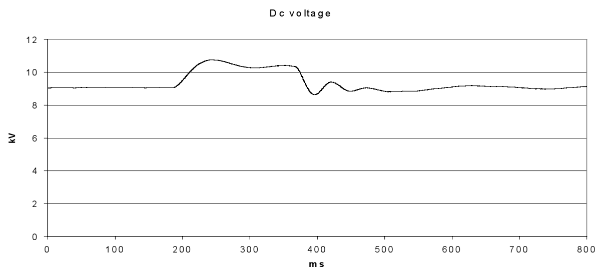


Figure 6 DC voltage at 180 ms temporary block of inverter.

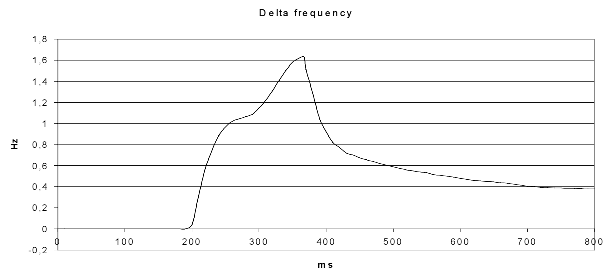


Figure 7 Delta frequency in the windfarm at 180 ms temporary block of inverter.

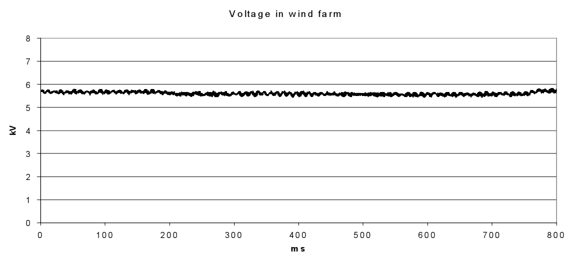


Figure 8 Voltage in the windfarm at 180 ms temporary block of inverter.

4. COMMISSIONING EXPERIENCE

During commissioning the static and dynamic performance of the HVDC Light is verified. Various tests were performed to investigate the behaviour and to prove the function of the VSC. The most interesting tests performed were:

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

4.1 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 (d.c.) mode the VSC absorbs the active power at the frequency selected by the operator. The a.c. 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.

4.2 Switching between the different operation modes with the a.c. and d.c. feeders

The power transmission from the windmills to the a.c. network can be done in three different operating modes, a.c. feeder only, d.c. feeder only or a.c. and d.c. feeder in parallel. Tjæreborg HVDC project 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 a.c. network can also be of interest, such as a radial interconnection of wind farms.

At low power the a.c cable is connected, and the VSC stations are connected but blocked, i.e. AC-mode. When the power increases the VSC stations are deblocked, the power in the d.c. feeder is increased until the current in the a.c. feeder is close to zero – Parallel-mode. Then the a.c. cable is disconnected and the wind farm is isolated from the a.c. network – DC-mode. At the isolation the VSC control in the wind farm is automatically turned into frequency and a.c. voltage control maintaining the frequency and voltage as prior to the isolation sequence.

When the power decreases below the pre-set level the frequency in the wind farm is synchronised with the a.c. network. The a.c. cable is reconnected and the VSC stations are blocked – AC-mode. This sequence is a completely automatic and very smooth, the transitions are hardly noticeable neither from the a.c. network nor from the wind farm.

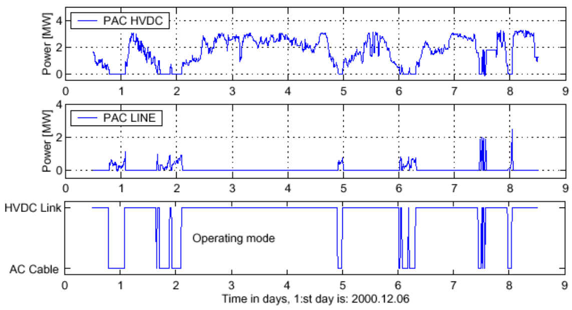


Figure 9 Transfer between a.c. and d.c. operation mode.

4.3 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 d.c. feeder is energised from Tjæreborg Substation, thus also the converter at Tjæreborg Enge is energised on the d.c. side. Deblocking Tjæreborg Enge gives the possibility to determine both the voltage amplitude and frequency at the wind farm. The a.c. voltage can be smoothly ramped up by the VSC thereby preventing transient over-voltages and inrush currents at energisation.

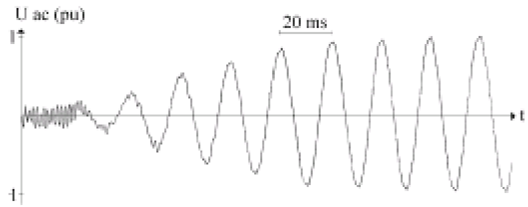


Figure 10 AC voltage at start-up of an isolated network (measurements from the Hällsjö project)

The windmills are automatically connected to the 10kV bus after seeing the correct a.c. voltage for 10 minutes. From their point of view there is no difference between being solely connected to the HVDC Light and to the a.c. network.

In some applications there may be no a.c. auxiliary power in the station before the converter is de-blocked, which means that the converter has to start up without cooling equipment, and as soon as the converter has started the valve cooling system can start up. The only auxiliary power required to start the isolated station is the power to the control equipment.

4.4 Varying the frequency in the wind farm

In isolated operation the Tjæreborg HVDC Light can vary the a.c. 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. Outside these frequencies the wind mills 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.

4.5 Verification of protection

A number of different protections are implemented to verify the safe operation of the VSC. The main part of the protections acts by tripping the station, i.e. blocks the converter and opens the a.c. breaker. As the VSC stations can act without communication with each other, the stations must be self-protecting.

During factory system tests and commissioning the function of all protections was tested.

4.6 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 criterion used was 42% of the totally allowed values in EN 50160. It also can be mentioned that the HVDC light does not contribute to the fifth harmonic distortion. Other nonlinear loads cause the fifth harmonic in the ac systems.

The recorded flicker value was Pst < 0.23 (95 % value) which is well below the normal limit of 1.0.

5. CONCLUSIONS

The Tjæreborg 8 MVA HVDC Light transmission based on VSC technique has been successfully commissioned. The HVDC Light concept works in accordance with the expectations.

The best principle found is to let the VSC rectifier works as a stiff voltage source at the reference frequency. The frequency reference can be set to the most optimal value. This means that the windmills see the VSC rectifier as a stiff ac network.

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 a.c. and d.c. transmission is performed completely automatic without any problem. The reason for the transition is loss minimisation.

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. In the future, when a large portion of the electric power generation consists of wind power, it is important that the windmills do not trip at disturbances in the receiving ac network. Therefore, there must be a certain margin between normal operation speed, and maximum transient overspeed, without any overspeed trip.

The agreement between simulations prior to commissioning, and the commissioning results has generally been very good. The only exception was that in simulation, dynamic frequency control worked properly for the studied cases. However, in practice the stiff ac network concept proved to be much more robust. The reason for this discrepancy is probably difficulties to properly simulate the dynamic of windmills, especially when provided with frequency converters. With the stiff ac voltage concept, the interface between the windmills and the VSC converters are simple and robust.

The experience from both commissioning and operation so far shows that HVDC Light transmission based on VSC techniques is a promising concept for connecting large wind farms to ac systems. However, at the design stage of the windmills the dynamic speed increase at ac system faults must be considered.

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