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DC FEEDER FOR CONNECTION OF A WIND FARM

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SUMMARY

A DC transmission link with 8 MVA Voltage Source Converters (VSC) will be installed in year 2000 for the connection of a 6 MW onshore wind farm at Tjæreborg in the western part of Denmark. It will investigate and demonstrate how to use a DC feeder to transmit power from the wind farm to the receiving AC grid. The drive for the project is that the Danish power utilities are planning to install five offshore wind farms of approximately 150 MW each.

A VSC with pulse width modulation can operate as rectifier or inverter at any frequency and at the same time absorb or supply reactive power to the AC network. A DC feeder with voltage source converters is therefore suitable for connection of wind farms with induction generators. The normal operation of such a link is to use frequency and voltage control in the converter connected to the wind farm. The VSC converter's ability to change the stator frequency of the induction generator gives the possibility to optimize the power output from the wind turbine by adjusting the frequency in relation to the wind velocity.

To verify the possibility and basic operation principles of operating a wind farm in a radial VSC HVDC connection simulations have been performed to test control algorithms, identify problems and investigate different modes of operation of the system and to demonstrate the unique capability of the VSC converters.

As VSC converters can be operated with variable frequency, it will be possible to control the speed of the wind turbines and by that the power production. With increasing amounts of wind power coming on line tendencies to reduce stability can be counteracted by DC transmission with VSC converters introducing damping characteristics.

Keywords: HVDC - voltage source converters - reactive power control - variable speed - wind turbines - induction generators - EMTDC simulations.

1. INTRODUCTION

The paper describes a demonstration project for installing and testing a DC feeder using an 8 MVA DC transmission link with Voltage Source Converters (VSC) for the connection of a 6 MW onshore wind farm at Tjæreborg in the western part of Denmark. The demonstration project is scheduled to be commissioned at the beginning of the year 2000. An investigation will be made of how the DC feeder may be used to transmit power from the wind farm to the receiving AC grid, and how the voltage source converter may be controlled in order to optimize wind power production.

The motivation for the project is that the Danish power utilities are planning to install five offshore wind farms of approximately 150 MW each. This is part of a plan to reduce CO_2 emissions. Within the next 30 years, the intention is to install 4000 MW offshore wind power plants, corresponding to 40%–50 % of the total installed capacity. Integration of huge quantities of wind power into the electrical power system may have severe consequences for that system. Fluctuating wind power production will replace the steady power production from conventional power plants, as well as their voltage control and contribution to the reactive power balance in the grid. Wind turbines with induction generators are very robust and require little maintenance and obtain their magnetization energy from the grid as reactive power, which influences power quality. With a DC feeder connection of induction generators, no reactive power will be obtained from the grid; only active power will be transmitted. Moreover, if the induction generators are connected with a DC feeder,

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the frequency in the wind farm may vary. Because of this, it may be possible to control the network frequency in the wind farm and the rotational speed of the wind turbines in such a way that utilization of the energy content of the wind is optimized [1].

A VSC with pulse width modulation can operate in all four quadrants of the PQ-plan; meaning that it can operate as a rectifier or inverter at any frequency, and at the same time, absorb or supply reactive power to the AC network. A DC feeder with voltage source converters is therefore suitable for connecting wind farms with induction generators. At the wind farm, the VSC can collect the active power from the induction generators, and at the same time, supply reactive power to the induction generators. Furthermore, the VSC can be operated at an optimal frequency.

Technically, a DC connection of offshore wind farms is a very interesting concept. As it has never before been done, it is important to test and evaluate the concept on a small wind farm onshore. Experiences from such a small demonstration project can be used to evaluate the merits of a DC feeder against those of an AC feeder in the connection of offshore wind farms.

2. THE TJÆREBORG WIND FARM

The Tjæreborg Wind Farm is in the western part of Denmark, on the West Coast. The wind farm consists of four wind turbines—one 2 MW turbine, two 1.5 MW and one 1 MW turbine for a total of 6 MW. The 2 MWwind turbine was built by the power utilities as a test installation and the results have been used by the Danish wind turbine manufactures in their efforts to further develop MW turbines. The wind turbine was connected to the network for the first time in 1988. Since the initial run in period, during which the control system and some of the main mechanical constructions were improved, it has been in normal operation. The other three wind turbines were developed by three Danish manufactures on specified terms. The wind turbines were erected between August 1995 and July 1996. Primary data are given in Table 1.

In order to limit output power and mechanical stresses on wind turbines, one of two major principles are used in controlling the turbines—either stall control or pitch control. Pitch control means that all blades can turn in relation to the wind. In this way, wind power is kept constant at a maximum permissible level, and the mechanical load on wind turbine components is limited. Stall control means that the blades are shaped in such a way that at wind speeds above a certain value—say 15 m/s—turbulence is created around the blades. Power capacity is then reduced and the transfer of wind power is kept at a constant level.

At the Tjæreborg wind farm, two of the wind turbines (TJ 2000 kW and Vestas V63-1500 kW) use pitch control whereas the other two wind turbines (BONUS 1.000 kW and NTK 1500/60) use stall control.

Table 1. Main data for the wind turbines.

Manufacture	**Tjæreborg prototype**	**Bonus**	**NEG-Micon**	**Vestas**
Electrical power (kW)	2.000	1.000	1.500	1.500
Rotor diameter (m)	61 m	54 m	60 m	63 m
hub height (m)	60 m	50 m	60 m	60 m
Speed of rotation (RPM)	22	22	19	21
Start wind speed (m/s)	5	3,5	4	4,5
Nominal wind (m/s)	15	15	16	15
Stop wind (m/s)	25	25	25	25
Type of regulation	Pitch	Stall	Stall	Pitch
Expected yearly production (GWh)	3.800	3.000	3.800	3.800

The duration curve for total power production in 1997 of the four wind turbines in Tjæreborg is shown in Fig. 1. Total production in 1997 was 11.2 GWh and the equivalent utilization time was 1,860 h (21.2 %). This corresponds to the time it would take to produce the yearly energy at full rated power (6 MW).

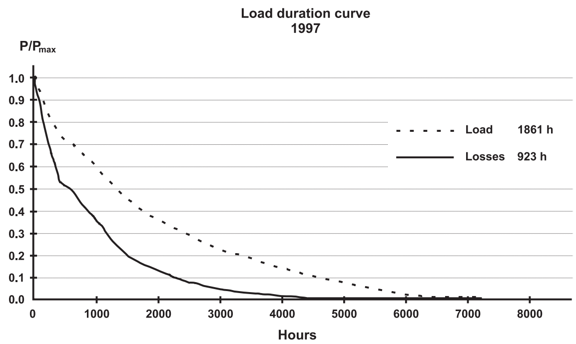

Fig. 1. Wind power production in 1997.

An electrical single line diagram is shown in Fig. 2. The TJ 2000 kW wind turbine has a 6 kV generator, and the other three turbines each have 0.69 kV generators. The voltages are transformed to 10 kV by transformers close to each of the wind turbines. The two 10 kV AC cable feeders are 4 km long and are connected to a 10/60 kV substation.

3. THE DC FEEDER

The DC feeder will be installed in parallel with the existing 10 kV feeders, see Fig. 2, so that it is possible to operate the wind turbines with the AC feeder alone, the DC feeder alone, or the AC and DC feeders in parallel. In order to investigate the possibility of operating the wind turbines at varying frequencies, a separate auxiliary AC supply will be provided for three wind turbines. They then may be operated at frequencies varying between 35Hz and 52 Hz, for example. Within this frequency band, frequencies that could cause mechanical resonance will be avoided.

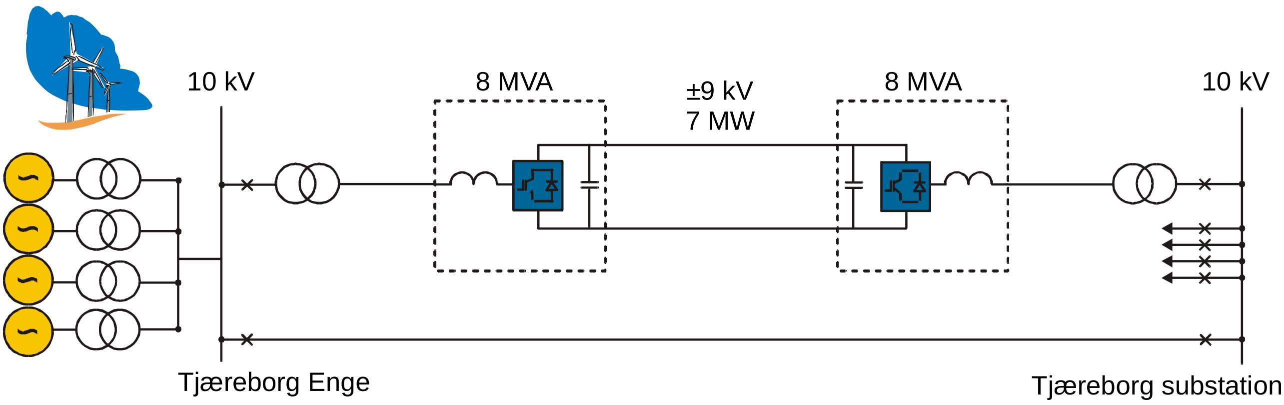

Fig. 2. Single line diagram of the AC and DC feeders.

The transmission rating of 7.2 MW corresponds to the normal power direction from the wind turbines to the AC substation. The converter stations are rated at 8 MVA. The DC feeder consists of two VSC stations (including filters, transformers, and cooling and auxiliary equipment) and a ± 9 kV DC cable with a length of 4.3 km. The VSCs are modularized, however, due to their placement in an open rural area all equipment at each of the VSC stations is placed in 16 x 22 meter buildings.

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 Figs. 3 and 4. With a small AC filter, the converter will fulfill the following performance indices up to 5 kHz, Dn ≤ 1 %, THD ≤ 5 %, TIF < 50.

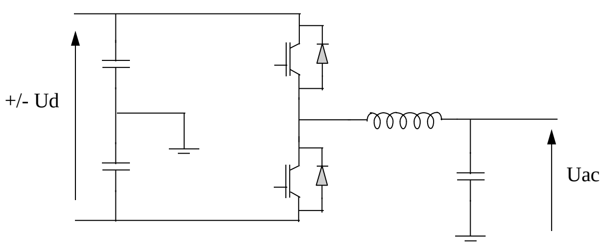

Fig. 3. One phase of the VSC with PWM.

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 [3]. 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 Fig. 5 (positive Q is fed to the AC network).

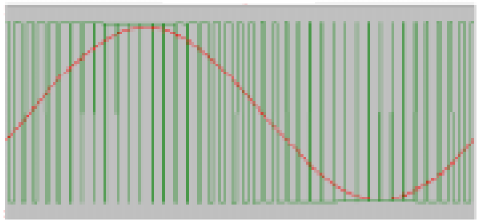

Fig. 4. The PWM pattern and the fundamental frequency in the VSC.

4. CONTROL PRINCIPLES

Induction generators absorb reactive power from the AC network for magnetization. The difference in frequency between rotor and stator determines the power output from the generator. When an induction generator is connected to the network, there is a large inrush of current to magnetize the generator. In a normal AC network, the frequency is fixed and the rotor frequency is not allowed to increase more than what corresponds to the peak in the torque characteristic. When the rotor frequency increases, the generator absorbs more reactive power and there is a risk for voltage collapse if the network is weak.

A VSC converter connected to a wind farm can supply reactive power to the induction generators independently of the active power it receives. It can also control the stator frequency freely and thereby the active power dynamically in such a way that the peak in the torque characteristic is not exceeded.

The power output from a wind turbine is given by:

$$P = \tfrac{1}{2} C_p(\lambda)\rho A V^3, \text{ Where}$$

A	is the swept area of the turbine blades
C_p	is the power coefficient of the turbine
V	is the wind velocity
ρ	is the air density

The power coefficient C_p determines the amount of kinetic energy from the wind that can be converted to wind power. C_p is a non-linear function of the ratio between tip speed of the turbine blades and wind speed. For each given wind velocity, the power coefficient has a maximum at

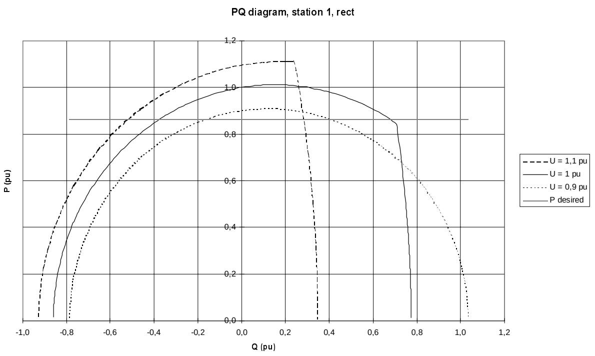

Fig. 5. P/Q-diagram for the DC transmission capacity from the wind turbine end.

which the windmill will produce a maximum power output as depicted in Figure 6.

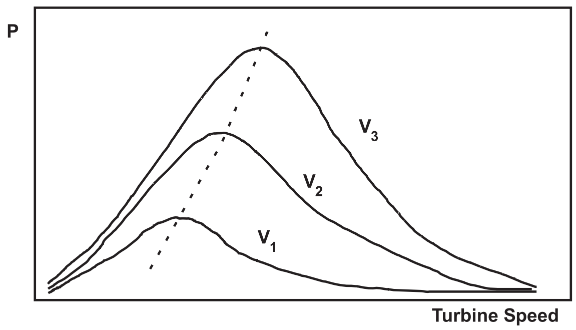

Fig. 6. Wind turbine power as function of turbine speed at various wind speeds.

The VSC converter's ability to change the stator frequency of the induction generator makes it possible to optimize the power output from the wind turbine by adjusting the frequency in relation to the wind velocity in order to obtain C_p-max. With only one VSC common for the four wind turbines a control strategy that will be pursued on this project is to track the best overall stator frequency.

When the DC link is connected to a wind farm with induction generators, normal operation is to use frequency and voltage control in the converter connected to the wind farm. The frequency control generates an active power order to the converter in order to balance the active power generated by the wind turbine. The voltage control generates a reactive power order to the converter in order to supply the appropriate amount of reactive power to the generator. In the converter connected to the AC network, DC voltage control is used to balance the active power received from the wind farm, and either reactive power control or voltage control can be used.

5. MODELING AND SIMULATION

To verify the feasibility and basic operating principles of wind farm operation in radial to a VSC HVDC connection, a model has been built in the EMTDC/PSCAD simulation program, modeling the wind turbines with correct aerodynamics and inertia dynamics. Modeling makes it possible to test control algorithms, identify problems and investigate different modes of operation for the system.

The control system of the model uses a variation of a classic type of space vector control such as vector transformations of the AC voltages, an outer control loop where AC and DC values are combined to calculate P and Q orders and generation of firings to the switching.

In Figure 7, a simulation is shown where five different events take place in the following sequence:

Period	**Time/sec.**	**Description**
1	0-0.5	Energization of the network AC side and the DC side
2	0.5-1	Energization of the wind turbine AC net work
3	1-2	Connection of two wind turbines at the same time and the last two wind turbines shortly after
4	10-15	Simulation of a drop in the windspeed
5	20-23	Lowering of the power production by lowering the frequency.

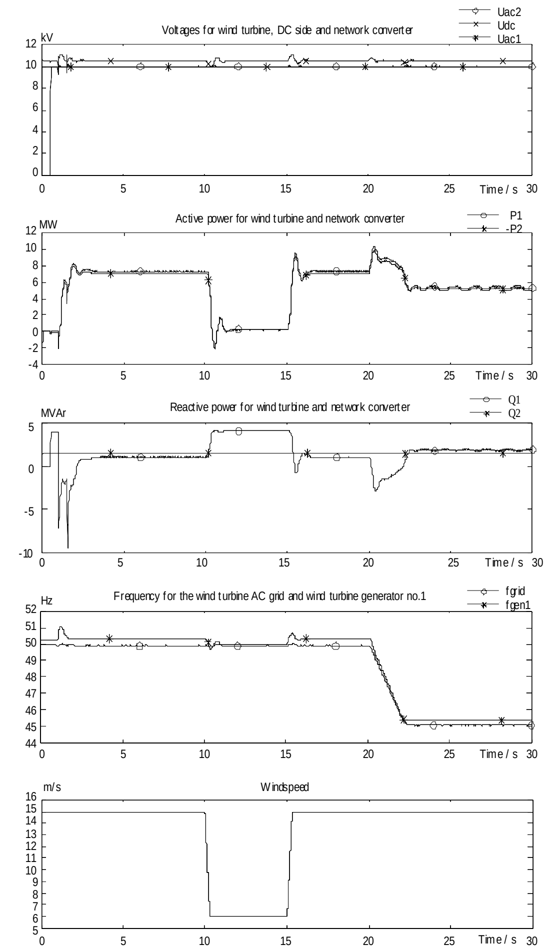

Fig. 7. Simulation of 5 different events. Index 1 designates wind converter. Index 2 designates returned converter.

Some of these events—such as a step drop in wind speed —are extreme compared to actual conditions, but are performed to demonstrate the unique capability of the VSC converters.

When a wind farm with induction generators is connected to a weak AC network, there is a risk for voltage collapse after a 3-phase fault, since the magnetization of the generators requires reactive power. With a DC link between the wind farm and the AC network, the wind farm becomes isolated from the AC network and is not seriously affected by the AC fault.

Figure 8 shows the result of a 3-phase fault, when the wind farm is connected directly to the AC network with the short circuit ratio of 4. The fault has a remaining voltage of 10% during 120 ms. The voltage never recovers and the rotor speed increases, causing the wind turbine to be tripped.

In Figure 9, the results are shown with the same fault, but with a DC link between the wind farm and the AC network. The voltage is not directly affected by the fault and the rotor speed is brought back to nominal by means of frequency control.

6. TRIAL AND TEST PROGRAM

The purpose of the trial and test program is to demonstrate performance—the robustness and capabilities of the system at various operation conditions, and contingencies such as recovery within 100 ms after AC network faults or after trips of one, some or all wind turbines. Also examined are: loading of the wind turbines or the VSC at both stations; operation of the VSC HVDC without communication between the two VSC stations; the active and reactive capability of the VSC; parallel operation of the AC and DC lines; start and stop of one or more wind turbines at various wind speeds; and operation at varying frequencies for the purpose of controlling the output power or to optimize overall energy production at various wind speeds.

7. FUTURE SYSTEM ASPECTS

Today, to protect the wind turbines, single wind turbines or smaller wind farms are allowed to trip even at small voltage and frequency deviations beyond a certain limit. For larger wind farms of 100 MW and higher, it is important that they remain online during temporary network faults in the same way as power plants. This new aspect is becoming important, as future wind power production will be aggregated in a few, very large offshore sites.

In future system operations, there will be stringent demands for additional primary and secondary frequency regulation strength and capacity. Because VSC converters can be operated at variable frequencies, it will be possible to control the rotational speed of the wind turbines and power production. For example, if 1 pu wind power is available but only 0.6 pu is needed, due to optimal sys-

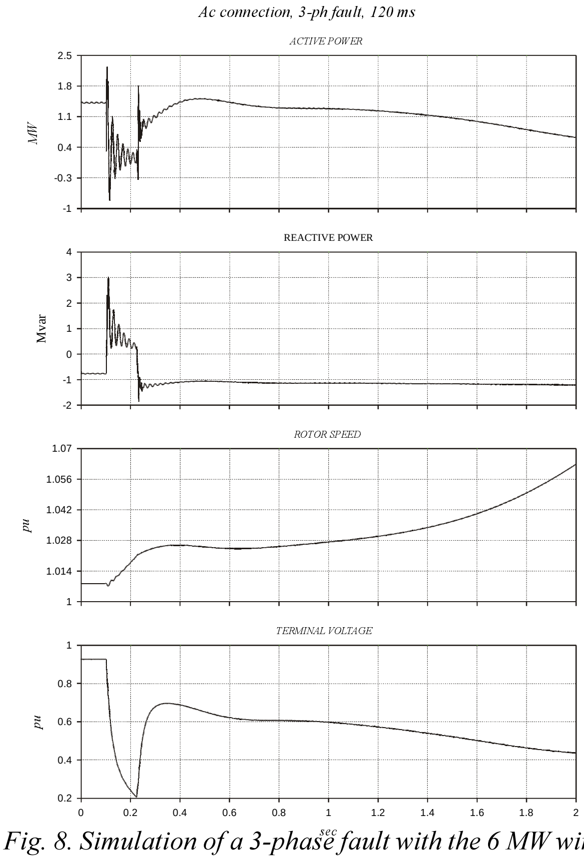

Fig. 8. Simulation of a 3-phase fault with the 6 MW wind farm connected to the AC feeder.

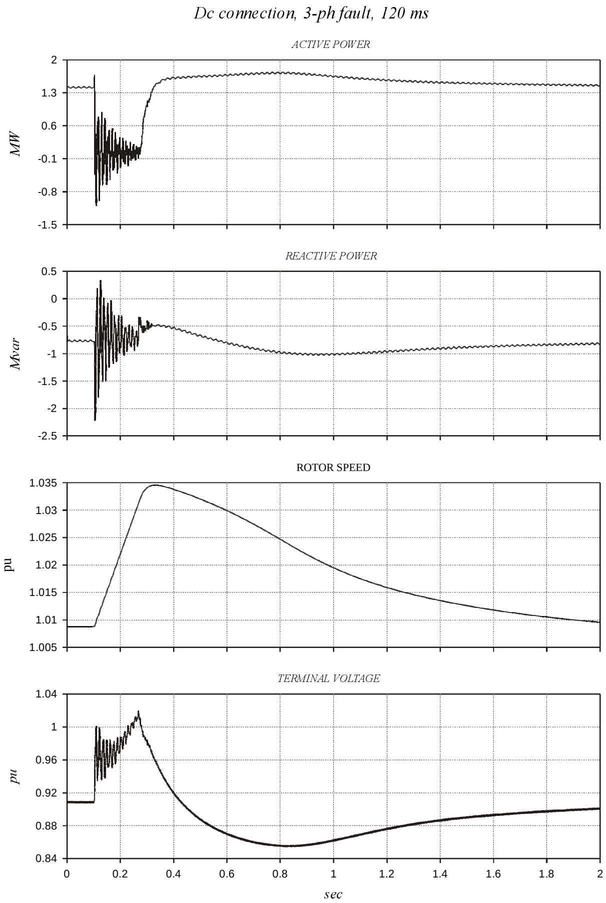

Fig. 9. Simulation of 3-phase fault with the 6 MW wind farm connected to the DC feeder.

tem operation, the frequency in the wind farm AC network is dropped as required. Due to the small time constants involved in wind power, there seems to be a potential for very rapid regulating gradients. This is a completely new way of thinking and brings greater value and flexibility to wind power.

Integration of a significant amount of wind power may lead to loss of synchronizing power and system damping, which causes problems with steady state and transient stability. With VSC converters, it should be possible to introduce damping and similar characteristics. Also, VSC converters are effective in flicker compensation, "black-start", island operation; controlled soft start and stop of the turbines; etc.

In general, it seem that VSC HVDC connections have a large potential for mitigating and limiting the non-ideal characteristics of modern wind turbines, and at the same time, adding power plant like characteristics to the network. One present drawback is the relatively high losses. However, the semiconductor development will reduce losses and eventually lead to further improvement of VSC HVDC technology

8. CONCLUSION

The preliminary studies and simulations of a DC feeder for the Tjæreborg wind farm have indicated that the concept is very promising. Several problems—e.g., voltage collapse, critical cable lengths, and wind power control—that may be crucial for large offshore wind farms can be solved. Additionally, application of DC feeders may improve the power quality from wind farms and may contribute significantly to improvement of overall system stability even with a high degree of installed wind power. That is, the use of VSC HVDC will make it possible to control the power production from wind farms and contribute to system frequency regulation. The demonstration plant at the Tjæreborg wind farm, with an 8 MVA VSC HVDC feeder, will be put into operation at the beginning of the year 2000. While continued development is foreseen, experiences from the plant can be used to evaluate this concept for the connection of offshore wind farms as an alternative to AC feeders.

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