ABSTRACT

The future for wind power generation in Germany is offshore wind energy. The preferred concept for power transmission over long distances from the offshore wind farm to the mainland is the High Voltage Direct Current (HVDC) power transmission. In this paper a new transmission concept based on HVDC is presented.

Keywords: HVDC, power transmission, thyristor, IGBT, VSC, offshore, wind farm, wind power, transmission line, wind park, distribution of electrical energy, power quality, Voltage Source Converter (VSC)

INTRODUCTION

Wind power is the world's fastest growing electricity generation technology, because wind power is a renewable energy resource of a high technical standard. The aim should be to replace conventional power stations supplied by fossil fuel with power plants based on renewable energy in the future.

The increase of onshore wind power generation in Germany has reached the maximum because there are only a few areas left to build wind power plants on the mainland. For the installation of the first German offshore wind farms already for a long time the permission is present, however all technical questions are not solved yet. One important task that has still to be solved is the power transmission from the wind farm to the mainland.

The preferred concept for power transmission from the offshore wind farm is the High Voltage Direct Current (HVDC) transmission, which is the best solution for long distances of power transmission. The losses of the HVDC transmission line are quoted as about 3% per 1000 km. The losses of the converter station are about 1.5% of the nominal transmission power [5]. Furthermore the HVDC allows the entire offshore wind farm to operate at a variable frequency, which can give some benefit in energy storage [2].
DIFFERENT HVDC CONCEPTS

Nowadays there are several HVDC transmission lines operating throughout the world. The main function for HVDC-systems is
− the transmission of energy over long distances and
− the connection of two a. c. grids with different frequencies.

If the transmission line is realized by submarine or underground cable, like it must be done offshore, the breakeven distance for HVDC-transmission compared to a. c.-transmission is much less than overhead transmission. It is not practical to consider a. c. cable systems for distances longer than 80 km but d. c. cable transmission systems are projected which length is in the hundreds of kilometres and even distances of 1000 km or greater have been considered feasible [3].

Another advantage of HVDC is the possibility of stabilization decentralized electric power grids. Some wide spread a. c. power system networks operate at stability limits well below the thermal capacity of their transmission conductors. HVDC transmission can be used to transfer directly to the energy to regions where the energy is consumed. So load of the existing grids will be reduced.

The HVDC power transmission can be realized in two different concepts. Today, the highest functional d. c. transmission is +/- 600 kV for the 785 km transmission line of the Itaipu scheme in Brazil. At present d. c. transmission is an integral part of the delivery of electricity in many countries throughout the world [3].

Thyristor-HVDC

The classic HVDC, that is used for some decades now, is based on thyristors as power electronics devices (Fig. 1). The thyristor-HVDC is a proven technology and available for transmission power up to some gigawatts. But the thyristor-HVDC has some disadvantages. The thyristor-rectifier and the thyristor-inverter need reactive power and filtering for an operation with good power quality. The grid-voltages and currents can be seen later in Fig. 3. It is also a problem to create a voltage-system offshore to supply the offshore wind park with energy during the installation, times of no wind and starting-up operation. The thyristor inverter needs reactive power for the commutation that has to be supplied by a strong supply grid or a reactive power source like a big synchronous generator that is connected to the offshore grid.
Fig. 1. Structure in Principle of Thyristor-HVDC

Fig. 2 shows the 6-pulse and 12-pulse thyristor units in detail.

Fig. 2. Thyristor-Unit (6-Pulse left, 12-Pulse right)

The thyristor-HVDC-Transmission is more expensive than a conventional a.c. solution for short distances. Nevertheless, HVDC may well be used for many offshore wind projects, because [2]:

- HVDC provides a power transmission with very high capacity over only two d.c. cables.
- HVDC has no restrictions for the transmission distance in principle.

In Fig. 3 the simulated voltage and the current of a thyristor converter are shown. The phase shift between the voltage and the current and also the harmonic content of the current can be seen.

Fig. 3. Simulation of voltage (in V) and current (in A) of Thyristor-Units (6-Pulse left, 12-Pulse right)
IGBT-HVDC

The fast changes in the field of power electronic devices with turn off capability like IGBT benefit the development of Voltage Source Converters (VSC) for HVDC applications. Fig. 4 shows a VSC-HVDC transmission, where the offshore IGBT-Unit rectifies the a. c. wind park voltages to get a d.c. voltage. The inverter onshore creates a three phase a. c. voltage to feed the energy into the public grid. In Fig. 5 you can see a IGBT-Units in detail.

![Fig. 4. Structure in Principle of IGBT-HVDC](image)

![Fig. 5. IGBT-Unit, (2-Level left, 3-Level right)](image)

The IGBTs switch fast between fixed voltage levels. The desired a. c. waveforms are reached by a pulse width modulation (PWM) and low pass filtering, which can be seen in the simulation in Fig. 6. So it is possible to create a voltage system offshore to supply the wind park with energy during installation and times of no wind. IGBT-HVDC provides independent control of reactive power at the converter stations, which could be a great benefit in increasing the power quality in the public grid. HVDC provides almost no contribution to fault currents, which in many areas are a major limitation on the connection of a new power station. In addition to full power flow control in both directions, the IGBT-HVDC system can prevent fault propagation, increase low frequency stability, reduce network losses and increase voltage stability. But on the other hand the power range of the IGBT-HVDC is only about some hundred megawatts, which is not enough for the big wind farms built in the North Sea.
The IGBT-HVDC-Transmission is still more expensive than the thyristor-HVDC relating to the same nominal power. Nevertheless the VSC-HVDC has some advantages for power transmission from offshore wind farms [2]:

- VSC-HVDC provides independent control of reactive power at the shore converter station, which could be a great benefit to the network operator, and could allow the network connection point to be on a weaker section of network, closer to the landfall.
- VSC-HVDC provides almost no contribution to fault currents, which in many areas are a major limitation on the connection of new generation of any type.
- The power flow can be realized in both directions.
- VSC-HVDC provides almost no contribution to fault currents, which in many areas are a limitation on the connection of new generation of any type (no commutation failures) [4].

The sinusoidal voltage and current of the IGBT converter are simulated in Fig. 6. There is no phase shift between the voltage and the current and the wave forms are sinusoidal.

**Fig. 6. Simulation of voltage and current of IGBT-HVDC**

**NEW SOLUTION**

There was shown in the previous chapter that the two described HVDC-concepts, the thyristor-HVDC and the IGBT-HVDC, have different advantages and disadvantages. The idea to get a power transmission system of high power capacity, good power quality and the possibility of energy supply for the offshore wind farm is the combined operation of the thyristor- and the IGBT-HVDC as can be seen in Fig. 7.

**Fig. 7. Parallel operation of thyristor- and IGBT-HVDC**
The two different HVDC concepts are connected on the d.c.-side by a circuit breaker to the HVDC transmission line so they are using the same d.c.-cable. At the a.c.-side the two concepts are connected by a transformer to the public grid or rather the offshore wind farm grid. The circuit breaker has to disconnect the IGBT-HVDC from the transmission line during maximum power transmission, because the d.c.-voltage level of the thyristor-HVDC is usually much higher than the voltage level of the IGBT-HVDC, for HVDC-System you can buy at the market. In this case the IGBT-inverters are operating as an active filter and are compensating reactive power of the thyristor units, as shown in the chapter “Compensation of reactive Power and harmonic content”.

One point, which is also interesting, is the so-called “black start” characteristics of the offshore wind park. It concerns to take the wind park from the switched off condition to the normal operation. Even if there is much wind, the wind energy stages need energy for the starting-up, in order to activate the auxiliary equipment such as cooling, oiling system, control etc. The IGBT-HVDC is able to generate an offshore voltage grid to supply the wind power plant with energy during this time. It is also necessary to supply the wind park for heating or rather cooling, control etc. in case of no wind.

OPERATION STRATEGY OF PARALLEL THYRISTOR- AND IGBT-HVDC

To optimize the parallel operation of the thyristor- and the IGBT-HVDC it is necessary to define different operation modes. There are shown two operation modes below:

Mode 1: Starting-up operation of the wind park and Power generation with partial load

- The IGBT-HVDC supplies the wind power plants with electrical energy and creates an offshore a.c. voltage grid.
  - onshore: d.c. voltage control
  - offshore: wind park a.c. voltage control (amplitude and frequency)
- The power transmission from the offshore wind park to the mainland is done by the IGBT-HVDC.
  - onshore: d.c. voltage control
  - offshore: wind park a.c. voltage control (amplitude and frequency)
- The Thyristor-HVDC is switched off.

![Fig. 8. Control mode of the parallel operation of thyristor- and IGBT-HVDC](image-url)
Mode 2: Power generation under full load (Fig. 11):
- The complete power transmission from the offshore wind park to the mainland is done by the Thyristor-HVDC while the HVDC voltage is set to maximum.
  - onshore: d.c. voltage control
  - offshore: d.c. current control depending on the wind offer
- The IGBT-HVDC is disconnected from the d.c.-line working as SVC (static var compensation).

![Fig. 9. Control mode of the parallel operation of thyristor- and IGBT-HVDC](image_url)

The correct function of the parallel operation of the thyristor- and the IGBT-HVDC could already be confirmed in simulations.

**Simulation Model**

The simulation model of the parallel operation of the thyristor- and the IGBT-HVDC can be seen in Fig.10. The different units operate with the following control strategy:
- Power transmission from the offshore wind park to the mainland is done by the Thyristor-HVDC and the IGBT-units are working as SVC (static var compensation).

![Fig. 10. Simulation Model of Parallel operation of thyristor- and IGBT-HVDC](image_url)
- The thyristor-offshore-unit controls the d.c. current and the onshore-unit the d.c. voltage.
- The IGBT-HVDCs are working as SVC (static var compensation) and compensate the reactive power and the harmonics of the thyristor-HVDC. The resulting a.c. offshore current can be seen in Fig. 11.

**Compensation of reactive Power and harmonic Content**

In Fig. 11 the simulation of the parallel operation of thyristor- and IGBT-HVDC can be seen. The IGBT-Converter acts like an active filter, so the reactive power is compensated and the harmonic content of the thyristor-HVDC is reduced.

![Fig. 11. Simulation of voltage (in V) and current (in A) of parallel operation](image)

**CONCLUSION**

The HVDC transmission is a good solution for connecting offshore wind farms to the mainland. In this paper two common concepts for realisation of a HVDC transmission were presented. The pros and cons were shown and an advanced concept for the realisation of an improved HVDC transmission line was presented. The operation modes were explained and the simulations were presented.

The results in this paper show that there are advantages to use the parallel operation of thyristor and IGBT-HVDC, like the possibility of power supply of the wind park, better voltage quality and a high transmission capacity with low losses.

**REFERENCES**


