CONTROL POSSIBILITY FOR OFFSHORE WIND FARMS

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Abstract – In this paper some of the most important issues for offshore wind farms like: wind turbines and connections to the system are presented. Different types of wind turbines with their main characteristics are given. As the most perspective wind turbine type for offshore wind farms, doubly fed induction generator (DFIG) has been detailed.

Existing connection technologies for power transmission from offshore wind farm to the system are discussed. From the technical and economical viewpoint and depending on the distance and power that has to be transmitted, solutions for possible connection technology are given. As very promising, especially regarding its technical features, the VSC-based HVDC technology is detailed. The possibility for the control of active and reactive power as well as its model is presented.

At the end different faults at one wind farm connected to the system are simulated and obtained results are given.

Keywords: Offshore, wind turbine, DFIG, connection, HVDC, modeling, control

1 INTRODUCTION

The wind energy is currently the fastest growing energy source in the World as well as in Germany. In 2003 in Germany were installed 2,65 GW of wind generators, which makes 14,6 GW of total installed wind capacity in Germany (Figure 1). Therewith is Germany the largest wind energy producer in the World. The main reason for such rapid growth is the application of Kyoto Protocol and German Renewable Energy Law (Erneuerbare Energie Gesetz - EEG). The growth is also strongly encouraged by the actual German Government which supports the retrieval from nuclear energy program.

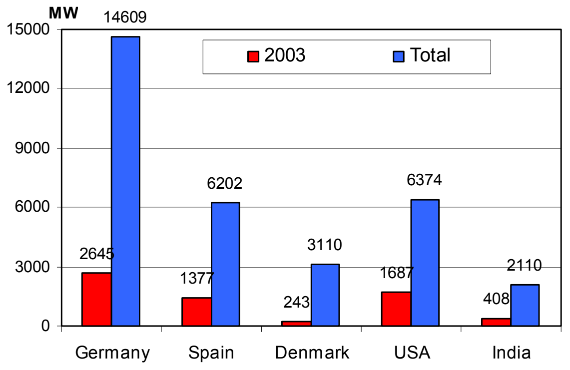

Figure 1: Installed and cumulative wind capacity in 2003 - top five

Primarily due to shortage of suitable sites on the land for wind generators and the fact that offshore wind energy resources are much higher than on the land, the offshore wind farm option as an electrical energy source has become very actual and attractive. The main advantage of offshore is based on the significantly higher and more constant wind speeds compared to the onshore [1, 2].

Regarding technical characteristics, there are several very important issues when planning an offshore wind farm. The objective of the first group is wind turbine/generator and it concerns the issues like: induction or synchronous generator, fixed or variable speed generators, pitch or stall control... [3, 4]. The other very important issue is the type of connection of offshore wind farms to the system. This question is lately becoming very interesting considering the large projected capacities (up to 1000 MW) of planned offshore wind farms and their increasing distances to the connection point to the system [5, 6, 7, 8]. The possible connections of offshore wind farms to the system are: HVAC, classical HVDC and Voltage Source Converter (VSC) based HVDC connection.

In the next chapter mostly used wind turbines/generators are described. In addition an electrical model of the DFIG as well as its control model are presented. In the following chapter the principal characteristics of different connection concepts are mentioned. Regarding the technical and economical aspects, the solution for possible connections is shown. In sequent chapter the VSC-based HVDC technology and its possibility for active and reactive power and voltage control is detailed. Finally, one wind farm connected to the system via VSC-based HVDC has been modelled and the simulation results of different fault behaviours are given.

2 WIND TURBINE SYSTEMS

The wind turbines are developing very fast, starting from a few kW up to more than 5 MW of installed power. Typical solutions for the wind turbines have been changed and improved in the history. Currently, following three wind turbine systems are mostly applied:

- fixed speed, stall controlled induction generator;
- variable speed, pitch controlled synchronous generator;
- variable speed, pitch controlled doubly fed induction generator (DFIG).

Fixed speed means that the rotor speed is directly connected to the system frequency and can not be changed. On the other side, variable speed means that rotor speed does not depend on the system frequency and can be changed.

With pitch control all blades can be put in such a way to keep wind power constant at a maximum permissible level. Therewith the mechanical load on wind turbine components is limited. By the stall control the blades are shaped in such a way to create turbulence around the blades above certain wind speed (e.g. 15 m/s). Therewith, the power capacity is reduced and the transfer of the wind power is constant.

2.1 Induction generator, fixed speed, stall controlled

This type (Figure 2) was mostly used in the past and is still used for the systems smaller than 1 MW. Its main characteristic is the fixed generator speed which means that the rotor speed is also fixed, i.e. directly coupled on the network frequency, and that it has a stall control of blades.

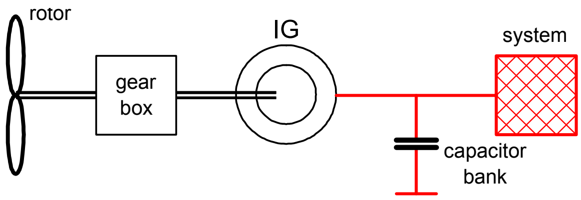

Figure 2: Fixed speed, stall controlled induction generator

Active power control is only possible by switching on/off of the wind turbine. Reactive power control is possible by using capacitor bank, voltage regulation can be obtained only with use of extra equipment, and the contribution of flickers and short circuit current is high.

Due to simple construction and low investment costs this system is very attractive for smaller wind turbines. The disadvantages of this system are the high demand on reactive power and very high starting currents. Therefore, the capacitor bank is a normal accessory for this system.

2.2 Synchronous generator, variable speed, pitch controlled

The wind turbine rotor is directly coupled with a rotor of synchronous generator. There is no need for a gearbox because a low speed multi pole generator is used. The generator is coupled to the system through voltage source converter, which transfers all produced power to the system (Figure 3).

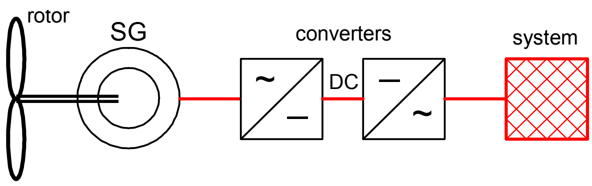

Figure 3: Variable speed, pitch controlled synchronous generator

The active power control is possible by pitch control (smaller changes), by converter control (larger changes) and by switching on/off of the wind turbine. Using voltage source converters the reactive power control is possible and, therewith, also the voltage control. Flicker contribution is low and, because of converter connection, there is no contribution to the short circuit current.

2.3 Doubly fed induction generator, variable speed, pitch controlled

The wind turbine rotor is connected via gearbox to the generator (Figure 4). The rotor of the DFIG is fed using a back-to-back voltage source converter, i.e. rotor is connected to the system through converters.

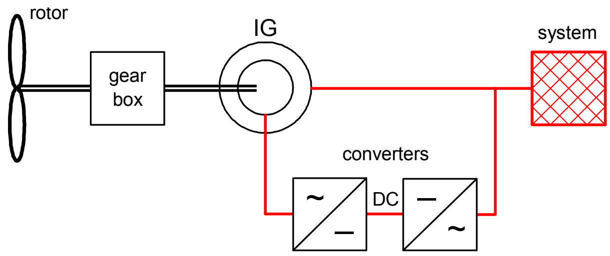

Figure 4: Variable speed, pitch controlled doubly fed induction generator

Because of its very good characteristics (active and reactive power control, voltage control, low flickers ...) DFIG is becoming the most popular wind turbine system, especially for offshore wind farms, where big wind turbines will be built. At the time, most wind turbine producers are focused on their development for the offshore implementation. Therefore, the model of a DFIG will be detailed in the next chapter.

3 DFIG MODEL

The mechanical power P_{mech} that turbine produces is:

$$P_{mech} = \frac{\rho}{2}\pi R^2 v_w^3 C_p(\theta,\lambda) \tag{1}$$

where ρ - air density; R - turbine rotor radius; v_w - wind speed; $C_p(\theta,\lambda)$ - aerodynamic efficiency which depends on the pitch angle θ and on the tip speed ratio $\lambda=(\omega_{rot}R)/v_w$, where ω_{rot} - turbine rotor speed.

The typical DFIG configuration is illustrated at Figure 5. The stator windings are connected directly to the system, but the rotor windings are connected through a back-to-back voltage source converter. The back-to-back converter is a bi-directional power converter which consist of two conventional pulse width modulation (PWM) voltage source converters (rotor side and system side converter) and a common DC bus. The transformer connecting DFIG to the system has two secondary; one winding connects the stator and the other the rotor.

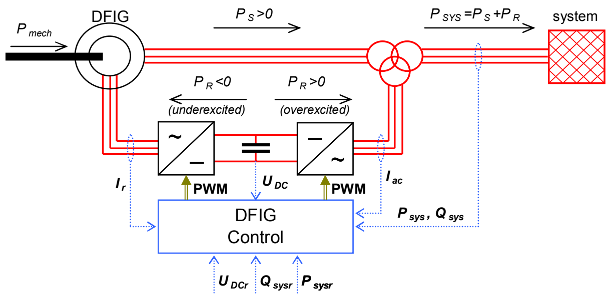

Figure 5: Doubly fed induction generator

The power converter provides the DFIG the ability of reactive power control. It decouples active and reactive power control by independent control of the rotor excitation current. Therefore, in the case of a weak grid, where the grid voltage may fluctuate, it is advantageous to use a DFIG. So, DFIG can produce or absorb an amount of reactive power for voltage control.

At the Figure 5 the DFIG control has been presented separate from the wind turbine control. As it can be seen, the control has been made by comparing the reference values (index *r*) and the measured values of active and reactive power, currents and DC voltage. Furthermore, at the Figure 6 the simplified power controllers of the active and reactive power at the rotor side have been presented.

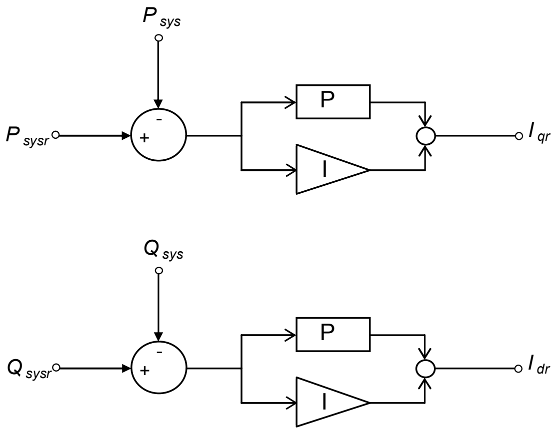

Figure 6: The controllers of the active and reactive power

By means of the bi-directional converter in the rotor circuit, the DFIG is able to work as a generator in both underexcited (positive slip s>0) and overexcited (negative slip s<0) operating area.

Assuming that all the losses in the stator and rotor circuit can be neglected, the power through the power converter P_R (rotor circuit), known as the slip power, can be expressed as the slip s multiplied with the stator power P_S. Furthermore, the delivered stator power can be expressed as dependent on the system power P_{SYS}:

$$P_R \approx - s\, P_S \tag{2}$$

$$P_S \approx P_{SYS} / (1 - s) \tag{3}$$

Depending on the operating condition of the converters, the rotor can be fed from the system or the rotor can fed the system. This means: the power is flowing from the system via converters to the rotor ($P_R < 0$) in underexcited mode; or vice versa ($P_R > 0$) in overexcited mode (Figure 5). In both modes the stator is injecting the power into the system ($P_S > 0$).

The DFIG can be mathematically described by steady state equations:

$$\overline{U}_S = (R_S + jX_S)\overline{I}_S + jX_M \overline{I}_R \tag{4}$$

$$\overline{U}_R = jsX_M \overline{I}_S + (R_R + jsX_R)\overline{I}_R \tag{5}$$

where

U_S, I_S, U_R, I_R - phasor's of the stator and rotor voltages and currents

R_S, R_R, X_S, X_R, X_M - machine resistances and reactance's

s - machine slip.

The solution of equations (4) and (5) may be written as:

$$\overline{I}_S = \frac{(R_R + jsX_R)\overline{U}_S - jX_M \overline{U}_R}{(R_S + jX_S)(R_R + jsX_R) + sX_M^2} \tag{6}$$

$$\overline{I}_R = \frac{(R_S + jX_S)\overline{U}_R - jsX_M \overline{U}_S}{(R_S + jX_S)(R_R + jsX_R) + sX_M^2} \tag{7}$$

The active and reactive power of DFIG that is supplied to the system is:

$$P_{SYS} = \frac{3}{2}\mathrm{Re}\{\overline{U}_S \overline{I}_S^*\} \tag{8}$$

$$Q_{SYS} = \frac{3}{2}\mathrm{Im}\{\overline{U}_S \overline{I}_S^*\} \tag{9}$$

4 OFFSHORE WIND FARM CONNECTIONS

As already mentioned, very important issue is the connection of the offshore wind farm to the system. The following offshore wind farm connections to the system are possible: HVAC, classical HVDC and VSC-based HVDC connection.

4.1 HVAC

This technology is simple and it represents a connection with sea cable up to 170 kV. Actual offshore wind farms and those planned to be commissioned in the near future have chosen HVAC for their connection to the system. Several advantages have driven these decisions. The main advantages are significantly lower costs comparing to the HVDC and large experience. The second reason is the fact that the power and the distance to the connection point to the system of these offshore wind farms are not so large and, therefore, the technical problems are not so serious. On the other hand, with the increase of power and distance, the reactive power compensation is required and the losses increase.

4.2 Classical HVDC

The thyristor based line-commutated converters HVDC technology can operate at up to 800 kV and its main advantage is the possibility of a large power transmission at large distance. Comparing with HVAC, this technology does not need reactive power compensation and the transmission losses are lower. Furthermore, this technology has other technical advantages like: possibility of active and reactive power control, variable operating frequency in the wind farm (decoupled from the system frequency), network decoupling by failure, reduction of the fault contribution etc.

The disadvantages of the classical HVDC are higher investment costs and the necessity for large converter stations offshore and onshore. Also, the auxiliary service at the offshore converter station for the operation of the line-commutated converters during wind still periods and power failures is needed. No experience in use of this technology for wind power transmission can be also named as a disadvantage.

4.3 VSC-based HVDC

The Voltage Source Converter (VSC) based HVDC technology represents an active system at 150 kV which uses the insulated gate bipolar transistors (IGBT) and pulse width modulation (PWM). The advantages of this technology like: possibility for active and reactive power control, network decoupling by failure, no need for an active commutation voltage, possibility for variable operating frequency in the wind farm (decoupled from the system frequency), reduction of the fault contribution etc. are making it very promising for the connection of offshore wind farms to the system, especially regarding the behavior of the wind power.

Very important feature from the system point of view is providing the auxiliary services to the system, i.e. possibility for reactive power and voltage control. This is very important in the circumstances where wind farms have to satisfy rigorous technical requirements. Also, in the future the large offshore wind farms will have to take part in overall system control and, therefore, the features that this technology is offering can be very important. On the other side, the same features can be very important for the wind farm, i.e. reactive power control within wind farm.

The main disadvantages of this technology compared to the HVAC solution are the investment costs, especially for the offshore and onshore converter station. Furthermore, due to the limitation in transistor technology it can not transmit very large amount of power as classical HVDC can. Also, the disadvantage can be that it has still not been applied for the large wind power transmission.

4.4 Combination of HVAC and HVDC

The combination of HVAC and HVDC solutions can be used for a very large offshore wind farms. Their commissioning is usually planned in two phases. The first phase or pilot project phase will be a relatively "small" wind farm (100 - 200 MW) and a HVAC connection should be expected. In the consecutive phase the total projected power should be built and than the use of HVDC can be expected. The HVDC can be added to the existing HVAC connection (Figure 7) or HVDC can take over the entire power transmission. Hereby, the existing HVAC cables can be used for HVDC connection.

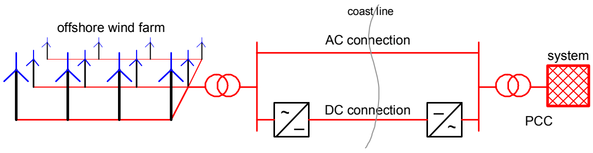

Figure 7: Combined HVAC and HVDC connection of an offshore wind farm

4.5 Solutions

From the above the following general approximation can be recommended (Figure 8):

- HVAC - for the small power and short distances;
- classical HVDC - for large power and long distances;
- VSC-based HVDC - medium power and longer distances.

It can be added that for the small offshore wind farms, which are relatively close to the connection point, the middle voltage AC solution can be used.

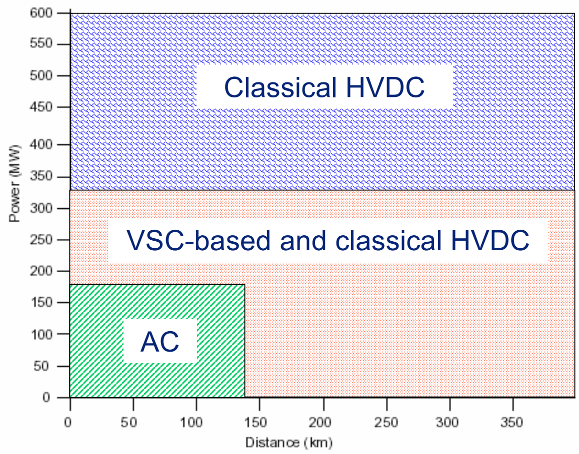

Figure 8: Connection technologies depending on the power and distance [5]

5 VSC-BASED HVDC - CONTROL MODEL

With the appearance of high switching frequency components like IGBT transistors it has become advantageous to use PWM technology. The AC voltage is created by very fast switching between two fixed voltages. The desired fundamental frequency of voltage is created through low pass filtering of the high frequency pulse modulation voltage (Figure 9).

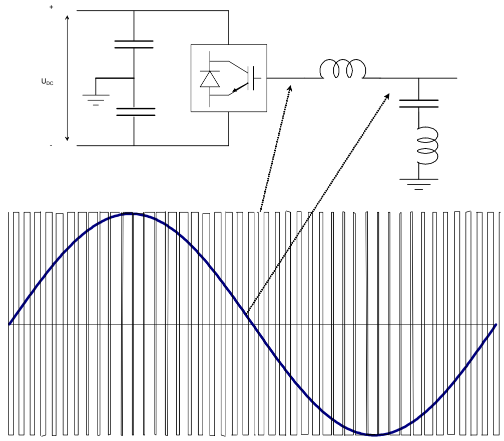

Figure 9: PWM pattern

PWM enables a creation of any phase angle or amplitude by changing its pattern. This can be done very fast, almost instantaneous. Therewith PWM represents excellent tool for independent control of active and reactive power. At Figure 10 the basic active and reactive power distribution by VSC-based HVDC technology is shown. Furthermore, the main equations describing the principles for active and reactive power control are given.

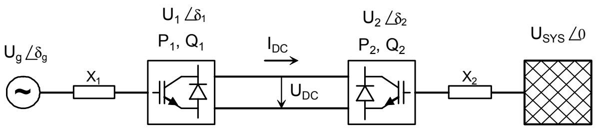

Figure 10: VSC-based HVDC - active and reactive power

$$P_1 = \frac{U_g \cdot U_1}{X_1}\sin(\delta_g - \delta_1) \tag{10}$$

$$Q_1 = -\frac{U_1^2}{X_1} + \frac{U_g \cdot U_1}{X_1}\cos(\delta_g - \delta_1) \tag{11}$$

$$P_{DC} = I_{DC} \cdot U_{DC} \tag{12}$$

$$P_{SYS} = \frac{U_2 \cdot U_{SYS}}{X_2}\sin(\delta_2 - 0) \tag{13}$$

$$Q_{SYS} = \frac{U_2^2}{X_2} - \frac{U_2 \cdot U_{SYS}}{X_2}\cos(\delta_2 - 0) \tag{14}$$

Power flow is achieved by controlling the phase angle of the AC side voltage of the sending converter (rectifier). Reactive power generated by the rectifier is controlled by adjusting the magnitude of the voltage on the AC side of the rectifier. DC voltage is controlled by adjusting the phase angle of the AC side voltage of the receiving converter (inverter). AC voltage magnitude at the receiving end is controlled by the inverter.

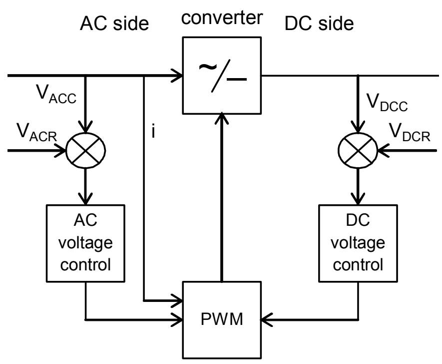

Figure 11: Control model of a VSC-based HVDC connection

As it can be seen at Figure 11, with PWM it is possibble to control both active and reactive power independently. Active power is controlled with DC voltage, and reactive by controlling the AC voltage.

This makes PWM VSC a close ideal component in the transmission network. From a system point of view, it acts as a motor or generator without mass that can control active and reactive power almost instantaneously.

6 SIMULATION RESULTS

In order to examine some of the above stated features of a VSC-based HVDC connection, one offshore wind farm with rated power of 100 MW was modelled. The offshore wind farm connection is VSC-based HVDC technology with 100 km submarine cable to the system. The nominal DC voltage is 150 kV. The ride through possibilities with different faults were simulated. The single phase short circuit near to the connection point at the system side has been observed. Also a single phase short circuit near to the generator (equivalent machine) on the wind farm side has been simulated. In both cases following variables have been observed: active power, reactive power and voltage at connection point (system side), DC voltage, and active and reactive power at the generator (wind farm side).

The simulations were made with electromagnetic-transient-digital simulator PSCAD/EMTDC. In simulation were used a library models of transformers, capacitors, coils and other electrical equipment.

At Figure 12 active and reactive power at the connection point (system side) are given. After a normal operating regime a single-phase to earth short circuit occurs at the system side at 2,5 s with fault duration of 100 ms.

For the same case, active and reactive power at the generator side have been presented at Figure 13. Furthermore, the voltage at the system side and DC voltage of HVDC link have been presented at Figure 14.

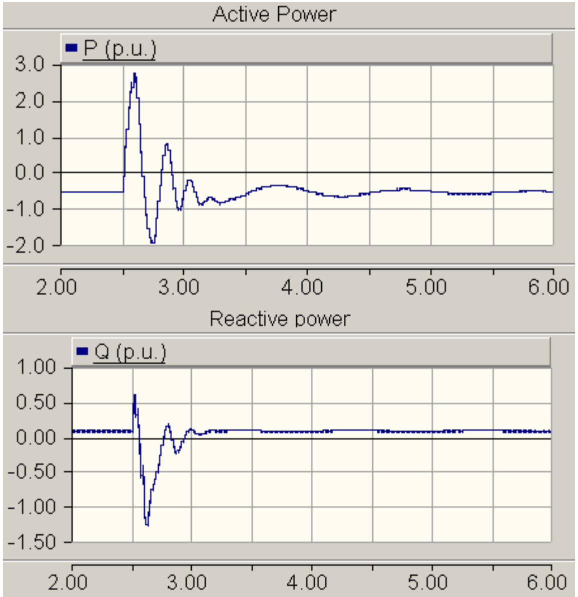

Figure 12: Active and reactive power at the system side after a fault at connection point - fault time 100 ms

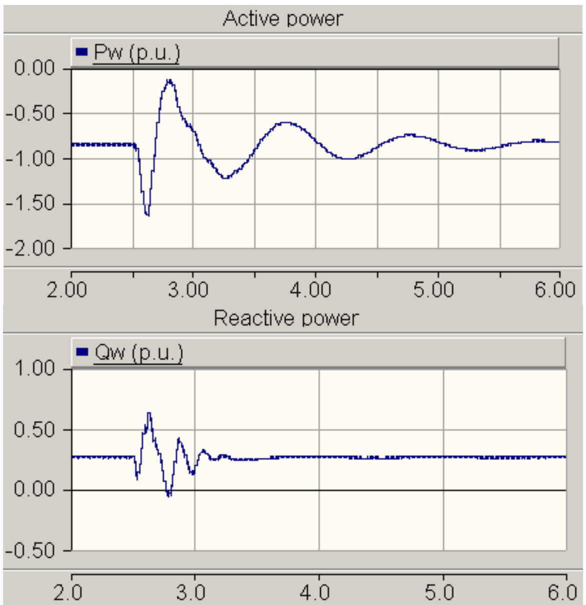

Figure 13: Active and reactive power at the generator side after a fault at connection point - fault time 100 ms

As it can be seen, all observed values (active power, reactive power and voltage) are becoming the pre-fault values, i.e. the observed system is staying in a stable operating regime. Figures 12-14 show that the wind farm and system maintain stabile after fault occurrence.

The active power at connection point has a strong oscillation as well as DC voltage. Both of them are recovering their values before the fault. The oscillation of reactive power and voltage at connection point of the system are not so strong because of damping of DC connection. As it can be seen at Figure 13, the impact on active and reactive power at the wind farm side is not so high.

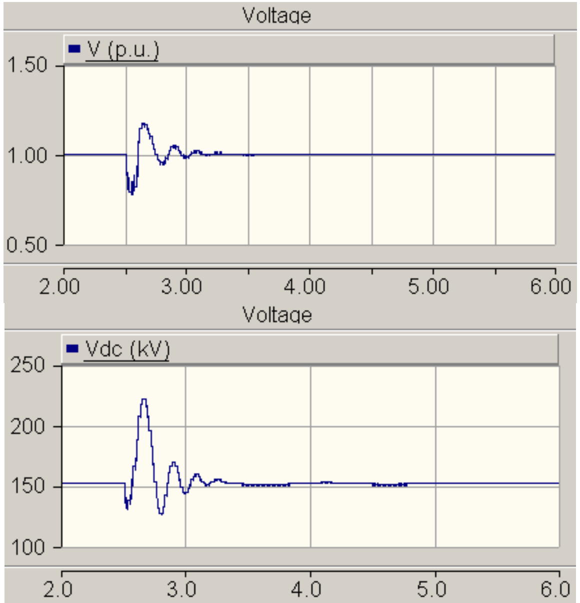

Figure 14: Voltage at system side and DC voltage at HVDC link after a fault at connection point - fault time 100 ms

At Figure 15 active and reactive power at system side have been presented. In this case a single-phase to earth short circuit occurs near to generator at 2,5 s with fault duration of 100 ms.

For the same case, active and reactive power of generator have been presented at Figure 16. Furthermore, voltage at the system side and DC voltage of HVDC link have been given at Figure 17.

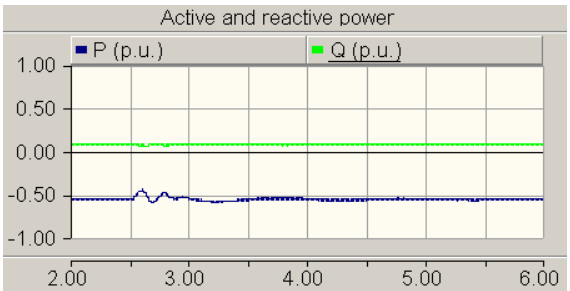

Figure 15: Active and reactive power at the connection point after a fault near generator - fault time 100 ms

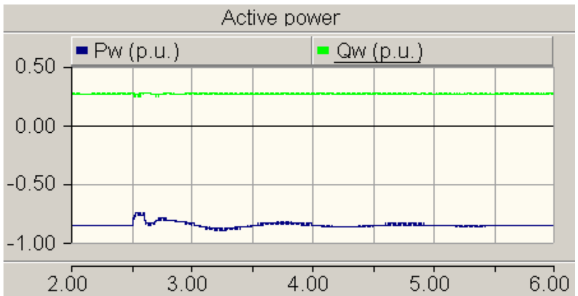

Figure 16: Active and reactive power of a generator after a fault near to generator - fault time 100 ms

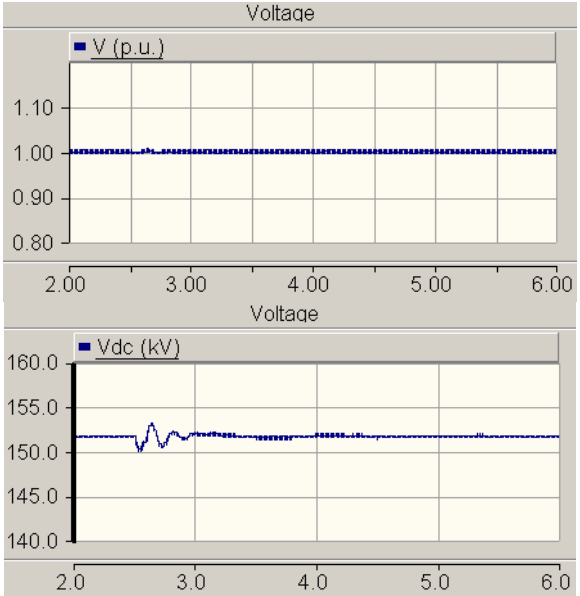

Figure 17: Voltage at system side and DC voltage at HVDC link after a fault near generator - fault time 100 ms

A fault near to generator (wind farm side) has only a minor impact on the system, i.e. there are some small fluctuation of active power and almost none of reactive power - Figure 15.

Active and reactive power on the generator (wind farm) side have been shown, a very small changes of observed variables are obtained - Figure 16.

Finally, the voltage at connection point has almost no change during and after the fault. As expected, like active power, DC voltage has also a small oscillation that are damped - Figure 17.

7 CONCLUSION

The connection of an offshore wind farm depends primarily on its installed power capacity and on distance to the connection point of the system. The advantages of using a HVDC solution are more significant with the increase of the power and distance.

The VSC-based HVDC technology represents very good solution for the connection of offshore wind farms to the system regarding: active and, especially, reactive power control, possible isolated operation, no need for an active commutation voltage etc.

With replacement of large synchronous generators, the issue of reactive power/voltage control is becoming very important, especially if the replacement will be mainly with wind generation. Therefore, the solutions like doubly fed induction generator and VSC-based HVDC connection represent a very promising solutions regarding their characteristics.

Modeling of a 100 MW wind farm connected to the system with VSC-based HVDC has shown that the system is stabile for applied faults, i.e. the ride through possibilities of the system are very good for observed cases. This is very important for the fault near to the connection point where larger oscillations have been obtained.

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