Integration of Wind Power into the German High Voltage Transmission Grid

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Abstract**-- This paper deals with the integration of wind power into the German high voltage grid. In Germany the installed wind power capacity already exceeded 19 GW and expected to reach 50 GW by the year 2020. For the connection of large offshore wind farms to the onshore AC grid DC transmission technologies can be used for which suitable submarine cables are necessary. German utilities defined grid code requirements on wind turbines spelling out the necessary grid-conform behavior. The most important obligations on wind generation plant operators concern fault-ride through and reactive power supply in steady state and during grid faults. The authors discuss the main issues contained in the revised German Grid Code released in 2006. For incorporating wind turbines and wind farms into power system stability studies, suitable models are presented. The behavior of a typical wind farm during three phase grid fault based on simulation results is shown.**

Index Terms**-- Wind power, control system, power system stability, doubly-fed induction machine**

I. INTRODUCTION

THE current German energy policy is focused on the large-scale utilization of renewable energy sources. Of the available alternative energy technologies, wind power seems to be the most promising one. By August 2006 the installed wind power in Germany surpassed the19-GW mark (Fig. 1). Most of the increase is expected to come from offshore plants but some growth is also predicted onshore as a result of the substitution of older wind turbines by larger and more efficient units. Today the nominal power of a single wind turbine has already reached 5 MW. The challenge now is to make wind turbines more robust for offshore operation and to meet grid requirements in steady state as well as in grid level emergency situation. Meanwhile wind turbine manufacturers continue to work on the development of even larger machines ranging up to unit sizes of 7-8 MW.

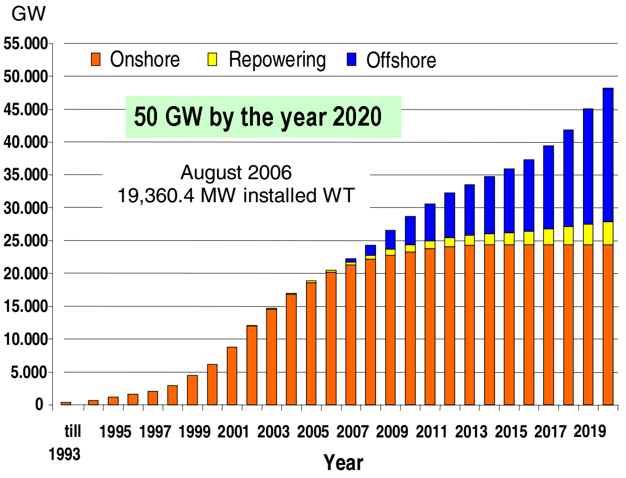

Fig. 1. Wind power utilization in Germany

With the increasing wind power utilization German utilities are faced with considerable changes in steady state as well as dynamic behavior of the power system. To identify future requirements and expectations major German utilities launched a joint comprehensive study called "dena-study" [1], which was completed in 2005. One of the concerns emanates from the inherent uncertainties associated with wind power generation. Despite some improvements, there is still a considerable error probability in wind speed forecasts requiring a significant increase in the short term reserve power capacity. Also, supplementary conventional power plants are needed for bridging periods with low wind power expectation. Furthermore, the existing high voltage grid must be extended for the integration of the upcoming wind power plants which are concentrated in the northern part of the country. Fig. 2 shows, the 400-kV-lines that need to be built in the next few years to meet the wind power transmission requirements.

The "dena-study" highlighted also the need for involving wind turbines into the overall reactive power generation and control process. All in all, it became obvious from the study that large wind farms have to behave pretty much like conventional power plants. In steady state they must be able to supply reactive power over a wide operating range depending on the requirements of the grid. Moreover, wind turbines have to stay connected to the grid during voltage dips and to provide, to the extent possible, voltage support.

As a consequence utilities decided to revise the existing grid codes to account for the increasing share of wind power generation and to consider new wind turbine technologies. E.on published the new grid code in April 2006 [2]. To assess the degree to which the wind turbines will affect the dynamic behavior of the power system, there is a need for suitable simulation models and tools. Utilities already require detailed

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1-4244-1298-6/07/$25.00 ©2007 IEEE.

dynamic simulation studies before the connection to the grid of several offshore wind farms, which are currently in the planning stage. Generally, simplified dynamic models must be made available to utilities to enable them carry out stability studies including the wind farms as part of whole system.

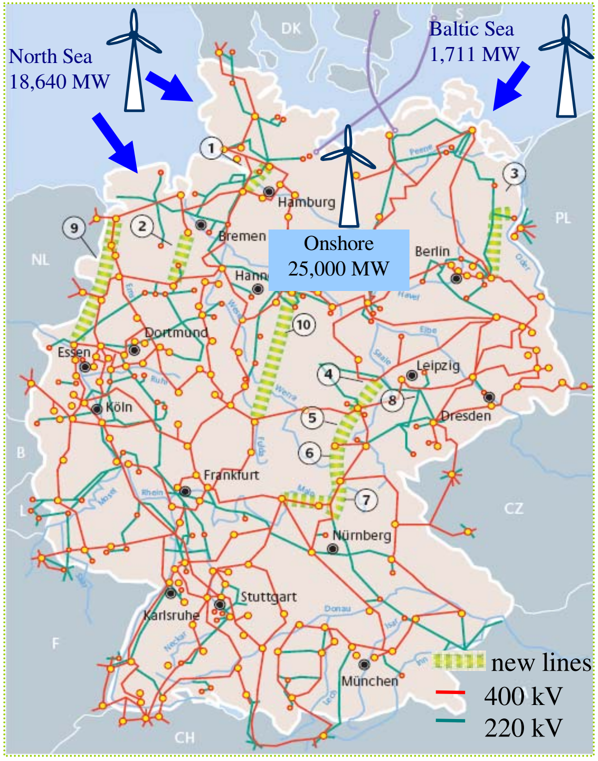

Fig. 2. Expected wind power in Germany by the year 2020 and 400 kV grid extension needed for wind power transmission

II. LINK OF LARGE OFFSHORE WIND FARMS TO THE GRID

Currently, in the German territorial waters of North and Baltic Seas, offshore wind parks are under development. In the initial pilot phase, typical capacities are 400 MW, but in the subsequent stages capacities of up to 1500 MW per wind farm are envisaged. The distance to the onshore point of connection to the transmission network ranges up to 150 km.

Concerning the transmission technology, different approaches are being discussed. Three-phase AC cables and the requisite auxiliary components (compensation) are proven to be available commercially. However, transport requirements of three phase XLPE AC cables are prohibitive, most of all as a consequence of restrictions on their physical dimensions. Fig. 3 shows the cross-section of a typical 150/170 kV cable. Key data predicating the technical feasibility are limited to a maximum copper cross section of about 1200 mm^2, cable diameter of more than 230 mm and a specific weight of about 100 kg/m. This results in a cable capacity of about 250 MVA, depending on the transmission range. For typical wind farms currently under development in Europe, this necessitates the use of two cables laid in two separate trenches. The cross-section of the 245-kV copper cable, currently being introduced to the market, is restricted to about 800mm^2, resulting in a maximum capacity of about 350 MVA. In summary, with the current state of the technology the technically feasible capacity limit for AC offshore transmission is about 370 MVA for 3-core cables and about 1000 MVA for three single-core 400-kV-cables [3]. Higher capacities at this point in time inevitably require more parallel cable systems. A new concept of bipolar transmission systems has been proposed in [4], where two XLPE single-core cables for each phase of the AC system are used. This single-core design permits the use of relatively high transmission voltages (for example, 400 kV) and maximum cross sections of up to 2000 mm^2, thus enabling a transmission capacity of up to 2000 MVA. The transmission range seems to be limited to about 150 km economically.

Alternatively, DC concepts have been a topic of discussion already for several years. Conventional, current source converters (CSC) based on thyristor switches have already been used for long distance, bulk electricity transport up to high voltage levels. Concepts adapted to offshore wind farms have been proposed in [4] but for a number of technical and economical reasons the prospects of these concepts asserting themselves are questionable.

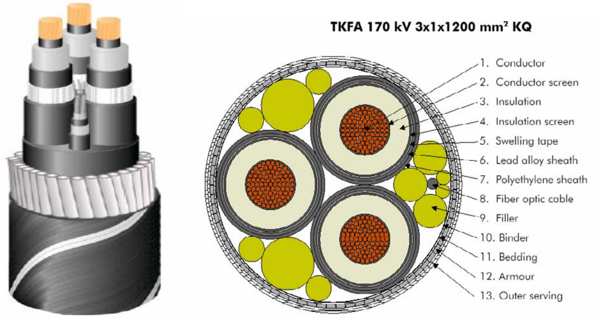

Fig. 3. Typical three core AC XLPE submarine cable for 150/170 kV, 3*1*1200 mm2; left ABB (FXBTV), right: Nexans (TKFA)

The capacity of commercially available IGBT based voltage source (VSC) converters has increased significantly during the past years. Converter capacities of up to 1100 MW reached the market [5], albeit from a limited number of suppliers (HVDC light, HVDC plus). Using state-of-the-art single-core XLPE DC cables (Fig. 4) with a rated voltage of ±150 kV and a cross-section of 2000 mm^2. The maximum capacity per circuit is about 400 MW. This would be sufficient, for example, for most pilot projects in Germany. Both DC cables can be laid together in the same trench. Limitations of this technology are the substantial costs for the power converters, the necessary space requirements, in particular offshore, and the conversion losses amounting to about 2…3% per converter.

Fig. 4. +/-150-kV XLPE-DC cable (source: ABB)

The number of potential projects under development in the North Sea points to substantial space requirements for cable routes. This is critically important as the coastal areas are sensitive and to a large extent declared natural parks and as such more or less protected. Consequently, planning and licensing of offshore routes is a complex and time consuming process with an uncertain result.

III. WIND TURBINE TECHNOLOGIES

To extract the maximum power, wind turbines need variable speed generators. The optimum rotating speed of the blades depends on the wind speed which varies over a wide range. On the other side the grid frequency to which the wind turbines are connected is nearly constant. Two basic principles of wind turbines have established themselves in multi-megawatt level wind power generation. The first and the most popular technology is based on the doubly-fed induction generators (DFIG). The rotor of the DFIG is equipped with three phase windings, which are supplied by a voltage source converter (VSC) of variable frequency and amplitude (Fig. 5).

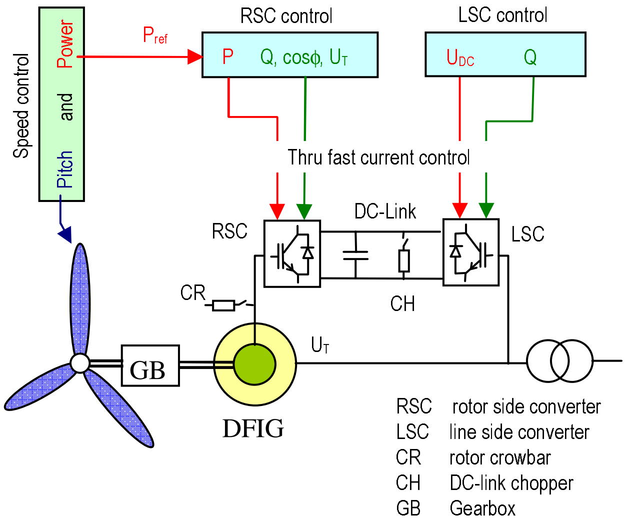

Fig. 5. Structure of the DFIG based wind turbine

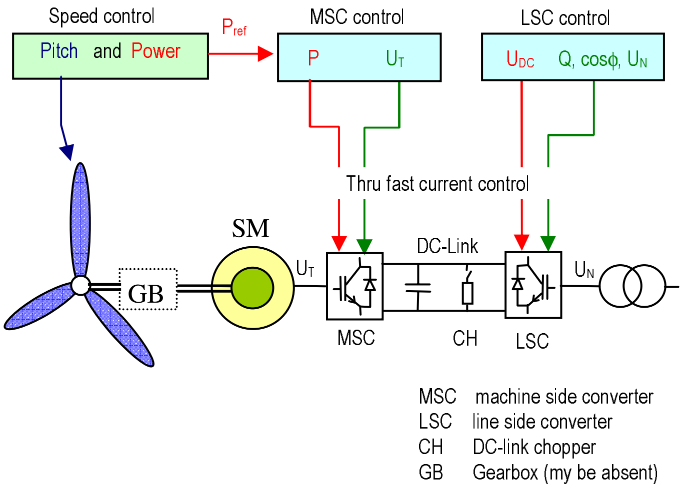

Fig. 6. Structure of the SM-based wind turbine with full size converter

The rotor speed varies in relation to the speed difference between the stator and rotor magnetic fields. The variability needed for wind turbines is usually restricted to ±30 % around the synchronous speed. The rotor power and thus the size of the converter is always below 30% of the wind turbine nominal power which is the main advantage of the DFIG based approach.

Variable speed wind generators can be built also with synchronous machines (SM) where decoupling to the fixed grid frequency is achieved by a full size VSC placed between the stator of the machine and the grid to which it is connected (Fig. 6). If the SM is equipped with an excitation winding and if the corresponding control keeps the terminal voltage at the nominal level, simple diode rectifiers can be used on the machine side. However, for wind turbines utilizing permanent magnets for excitation generation of the reactive power required by the SM. presupposes a controlled converter.

The gear box, which is one of the most stressed components in wind turbines, adapts the rotating speed of the turbine blades to the much higher generator speed. However, it is also possible to build wind turbines without gearbox, but this calls for a much larger number of poles and thus necessitates a greater machine size.

Wind turbine control consists of two parts, one for pitching the rotor blades when the nominal wind speed is exceeded and the other for fast electrical converter control. The converter control provides the freedom for independent control of active and reactive currents and thus the corresponding power.

Active power exchange through the DC-link is ensured through the control of the DC-voltage. The IGBT converters can also be used to generate reactive power needed for the generator's own consumption but also for supply into the grid. Reactive power generation in the DFIG is more suited using the rotor side converter on account of the fact that the current turns ratio between stator and rotor is about 3:1. However, it is also possible to use the line side converter as long as the active power can be fully passed trough the converter. Also, wind turbines with full-size converter provide excellent reactive power control capabilities on the grid side. The reactive power, the power factor or the terminal voltage can be used as alternative control variables, whereby the last option represents direct voltage control.

IV. GRID CODE REQUIREMENTS

In the following sections the German grid code will be discussed with focus on wind farm operation in steady state and during grid faults.

A. Steady State Operation

The generated wind power has always transit priority. So the variable generation in the system has to be guaranteed by conventional generators. Restrictions on wind power in-feed are only allowed if it leads to transmission line overloading. As regards the necessary reactive power supply, utilities defined the required range in terms of power factor in relation to the voltage at the point of common connection (PCC) with the grid. Figure 7 shows the structure of a typical wind farm connected to the grid through an AC cable including alternatives for reactive power generation.

Long AC cables always require compensation by shunt reactors on both sides. To avoid periods without inadvertent compensation, fixed connection of reactors in both ends of the cable is recommended so that the cable and reactors will always be switched together. The cable itself represents a reactive power source that injects reactive power into the grid.

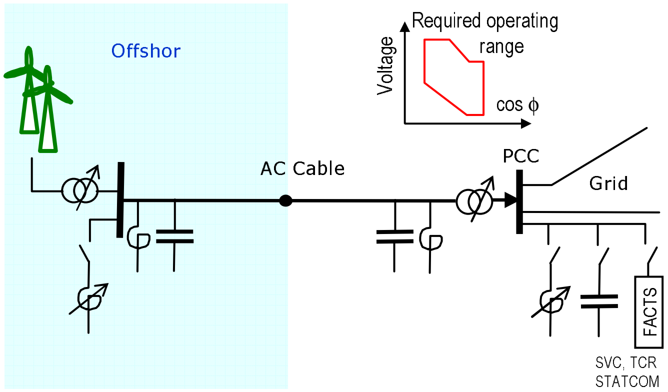

Fig. 7. Alternatives for reactive power generation

With slightly under-compensated cables it is possible to provide a considerable contribution to the overall var generation without facing any technical problems. In some cases additional compensation devices connected to the PCC and to the offshore platform might be needed. To provide flexibility with minimum space requirements, it is also possible to use shunt reactors equipped with tap-changers. Wind turbines can supply/absorb reactive power within a range of ± (0.9 – 0.95) power factors even when the maximum active power is generated. With reduced active power output the var capability of wind turbines will obviously increase further. Investigations have shown that reactive power transmission from the wind farm to the grid may be desirable despite the accompanying losses.

FACTS may be an interesting alternative especially under power system dynamic aspects. However, until now FACTS devices remain the last resort for reactive power generation on grounds of cost.

B. Behavior of Wind Turbines during Grid Faults

In the past wind turbines were disconnected from the grid following grid faults. However, as of now, this will no longer be permitted as the separation of wind turbines each time the voltage dips below 80% of the nominal voltage would lead to an intolerable loss of generation. Therefore, utilities require fault-ride through (FRT) capabilities that is specified in Fig. 8. Wind turbine must stay connected even when the PCC voltage is zero. The 150 ms accounts for typical operating time of protection relays. The red solid line in Fig. 8 marks the lower voltage boundary rather than any characteristic voltage behavior.

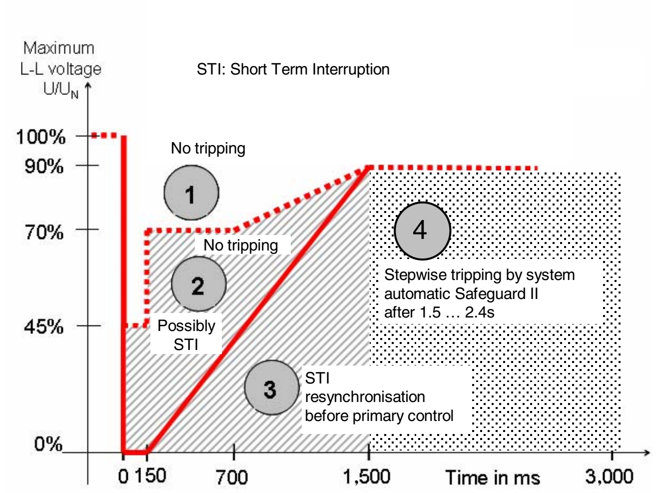

Fig. 8. Fault-ride through requirements

According to the new E.on grid code of 2006 [2] short term interruption (STI) is allowed under specific circumstances. STI in area 3 (see Fig 8) requires resynchronization within 2 s and power increase rates of at least 10% of the nominal power per second. In area 2 the interruption time allowed is much less, amounting to just a few hundred milliseconds. Besides, forced reactive power supply is required during this period. DFIG based wind turbine can, for example, fulfill these apparently conflicting requirements by controlling the grid side converter for maximum reactive power generation while the stator remains disconnected.

According to the German grid code wind turbines must provide, as a mandatory requirement, voltage support during voltage dips. The corresponding voltage control characteristics are summarized in Fig 9. According to this stipulation wind turbines have to supply at least 1.0 p.u. reactive current already when the voltage falls below 50%. A dead band of 10% is introduced to avoid undesirable control actions. However, for wind farms connected to the high voltage grid continuous voltage control without dead band is also under consideration.

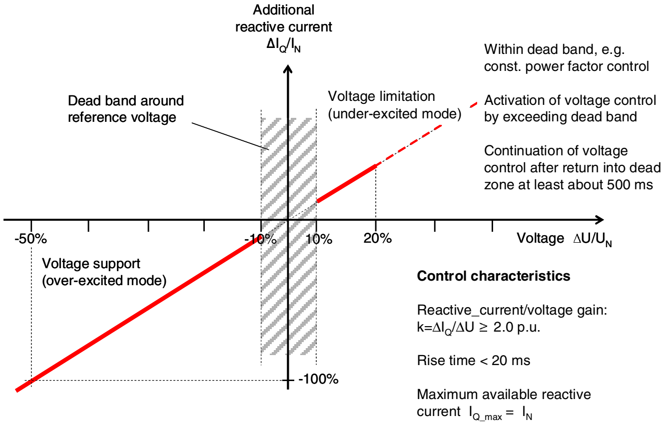

Fig. 9. Characteristic of wind turbine voltage control

The latest E.on grid code has also defined consequences for non-compliant behavior by wind farms. As shown in Fig. 9 when the voltage remains below 85 % and the wind farm still doesn't supply the reactive power required for voltage support, safeguard I implemented in PCC will trip the wind farm after 0.5 s. Safeguard II at the wind turbine level is implemented as system protection acting after 1.5 s and includes the stepwise tripping of wind turbines.

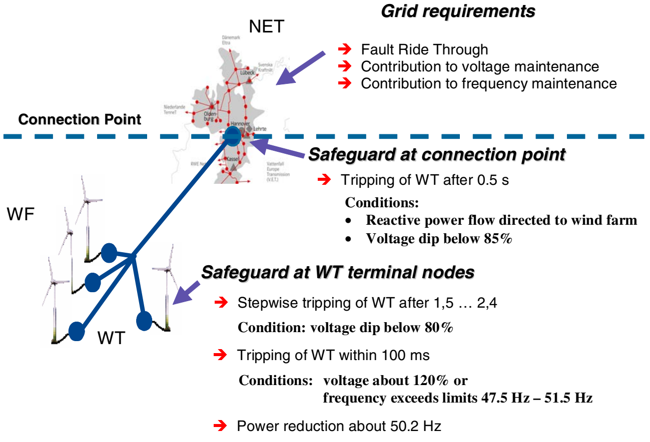

Fig. 10. Definition of safeguard functions

V. Model of the DFIG based Wind Turbine

With the increasing utilization of wind power it became obvious that stability kind of simulation studies have to be extended to include wind turbines and their impact on power systems. However, simulation models used by manufacturers for design and verification purposes are too complex to be used in large scale power system simulations. Therefore, in the last few years intensive research has resulted in simplified models allowing the simulation of hundreds of wind turbines together with a large number of conventional power plants [6]-[10]. In this chapter as an example, models of the DFIG based wind turbines will be introduced.

A. *DFIG Model*

The derivation of the DFIG model is shown in detail in [11]. The basic simplification comprises neglecting the transient components in the stator voltage equation. This step results in a complex algebraic equation for the stator circuit that can be incorporated into the grid equations. The remaining three differential equations describe the rotor flux in direct (d-) and quadrature (q-) components and the rotor speed so that the model is of 3rd order. Fig. 11 shows the structure of the model and the couplings to the grid, converter and pitch/speed control parts. The DFIG is coupled to the algebraic grid equations through its Thévenin equivalent where the voltage source (EMF) is a function of the rotor flux components that are state variables.

B. *Rotor Side Converter Model*

The rotor side converter (RSC) supplies the three phase rotor circuits of the induction generator through slip rings. The RSC model is shown in Fig. 12. Detailed description can be found in [11]. It comprises two control channels, one for active and another for reactive power. The inner control loops are realized as current control.

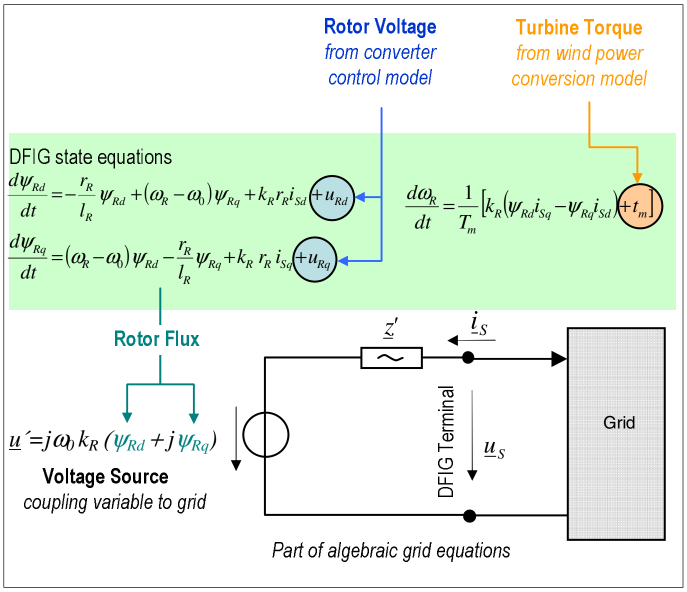

Fig. 11. DFIG model

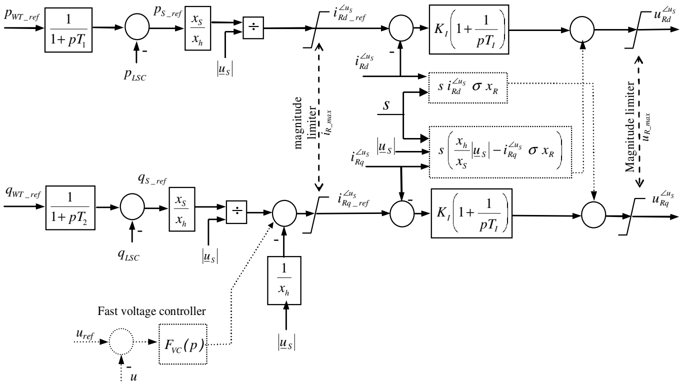

Fig. 12. Rotor side converter model

The magnitude of the rotor current reference is limited by the IGBT rating. However, following grid faults the actual rotor current may increase above the limit so that it is necessary to stop the RSC. Nevertheless, the current continues to flow through freewheeling diodes into the DC link. Subsequently the DC voltage will increase further. Limitation of the DC voltage is accomplished by a DC chopper and/or by the rotor crowbar. The chopper is a resistance that is switched on when the voltage exceeds a certain limit. Sometimes the chopper is not effective enough to limit the DC voltage. In this case the RSC is separated from the rotor and the rotor crowbar is fired. After a predefined time the crowbar is switched off and the RSC is started again. This FRT procedure is essential to meet grid code requirements. A more detailed description of FRT with DFIG wind turbines can be found in [12].

Input variables of the RSC control as shown in Fig. 12 are the wind turbine active and reactive power. The active power reference is provided by the speed/pitch-angle control that adapts the generator speed and blade pitch-angle to varying wind speed conditions so that always the maximum power is extracted. The reactive power reference can be freely chosen within some limits.

C. LSC Model

The line or grid side converter (LSC) controls the DC voltage and thus the power flow through the DC-link. A simplified model is shown in Fig. 13. The reactive power control loop can be used as long as the LSC current limitation is not reached. However, active power transfer through the LSC has always priority over the reactive power.

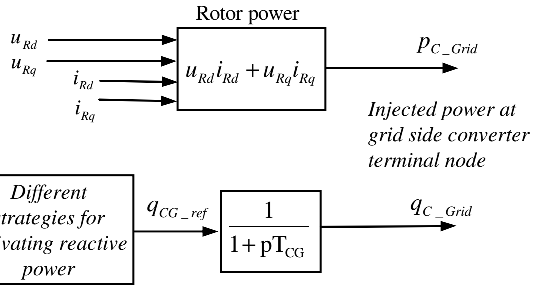

Fig. 13. Line side converter model

D. Speed/pitch- angle control and model of the wind power conversion

The speed control has to adapt the wind turbine speed to the actual wind speed in such a way that always the maximum power is extracted from the wind. The rotating generator speed can be controlled through the reference power passed to the converter control and through the pitch angle. Below the nominal wind speed the blades are fixed at the position of maximum power generation. The speed is controlled along a characteristic power/shaft-speed diagram. When the wind speed exceeds the nominal value the blades are pitched for keeping the generated power constant at the nominal power. A simplified control diagram developed for a 5MW wind turbine is shown in Fig. 14.

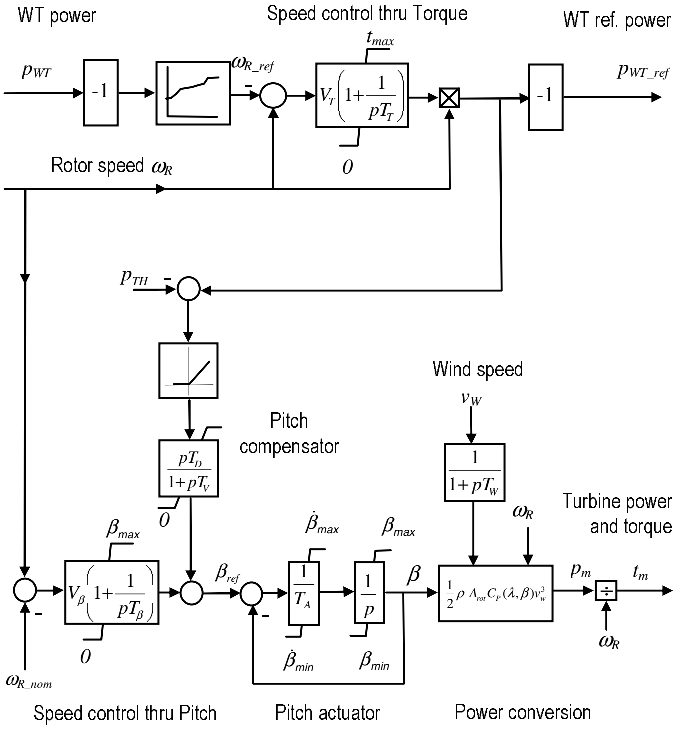

Fig. 14. Speed/pitch- angle control and model of the wind power conversion

To verify the model wind ramps from 10 m/s to 14 m/s and back to 10 m/s after further 25 s have been calculated with the simplified model and also with a detailed model of the manufacturer used for design purposes. The results are shown in Fig. 15. In the range from 10-14 m/s the nominal power generation and thus the nominal speed are reached. Further increase of the speed must be limited by pitching the rotor blades. This change between the operating modes represents a challenge for the controller applied. As can be seen from the diagrams the simplified model provides an excellent accuracy from the practical point of view justifying its use in power system dynamic studies.

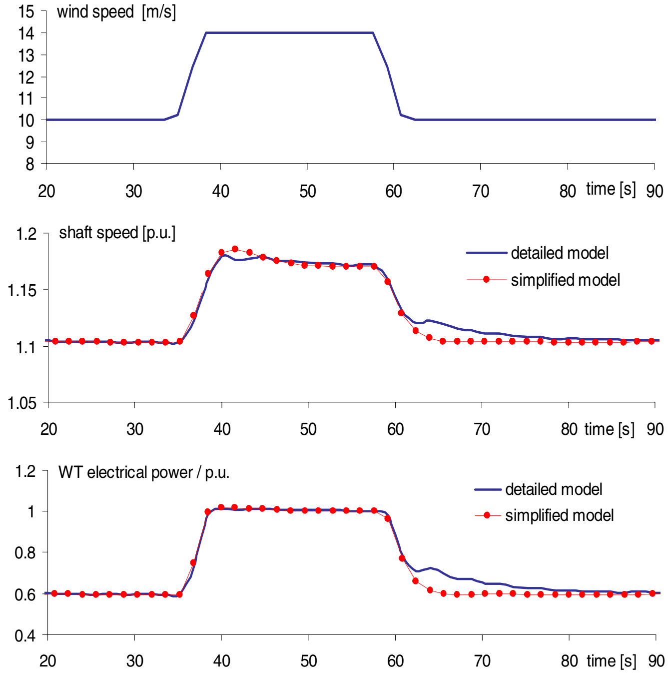

Fig. 15. Response of the wind turbine model to wind ramps

VI. WIND FARM SIMULATION EXAMPLE

In future wind farms with hundreds of megawatts capacity are likely to be built offshore. Many of these wind farms currently under investigation are located more than 100 km away from the PCC. The operational performance of the underground/submarine cables to be used to transmit the wind power to the grid and the operation of the wind farms themselves represent a technical challenge for which one has no experience to fall back on. Special interest is focused on the dynamic response of wind farms to grid faults. The example shown in this chapter demonstrates the behavior of DFIG-based WT following a three-phase short circuit in the 380-kV-grid that results in a voltage dip below 10% in the connection point. Fig. 16 shows the structure of the wind farm simulated.

Results are compiled in Fig. 17. The length of the two 150 kV transmission cables is about 144 km, which is already close to the possible technical limit. Shunt reactors are connected to both ends of the cable for compensation purposes.

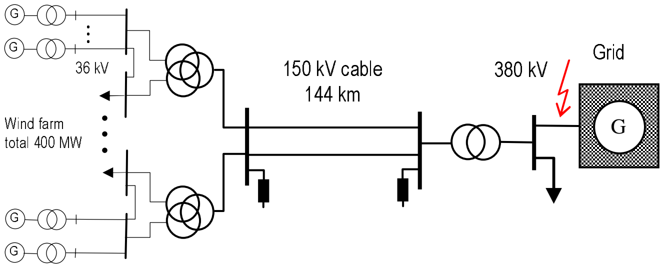

Fig. 16. Simulated offshore wind farm

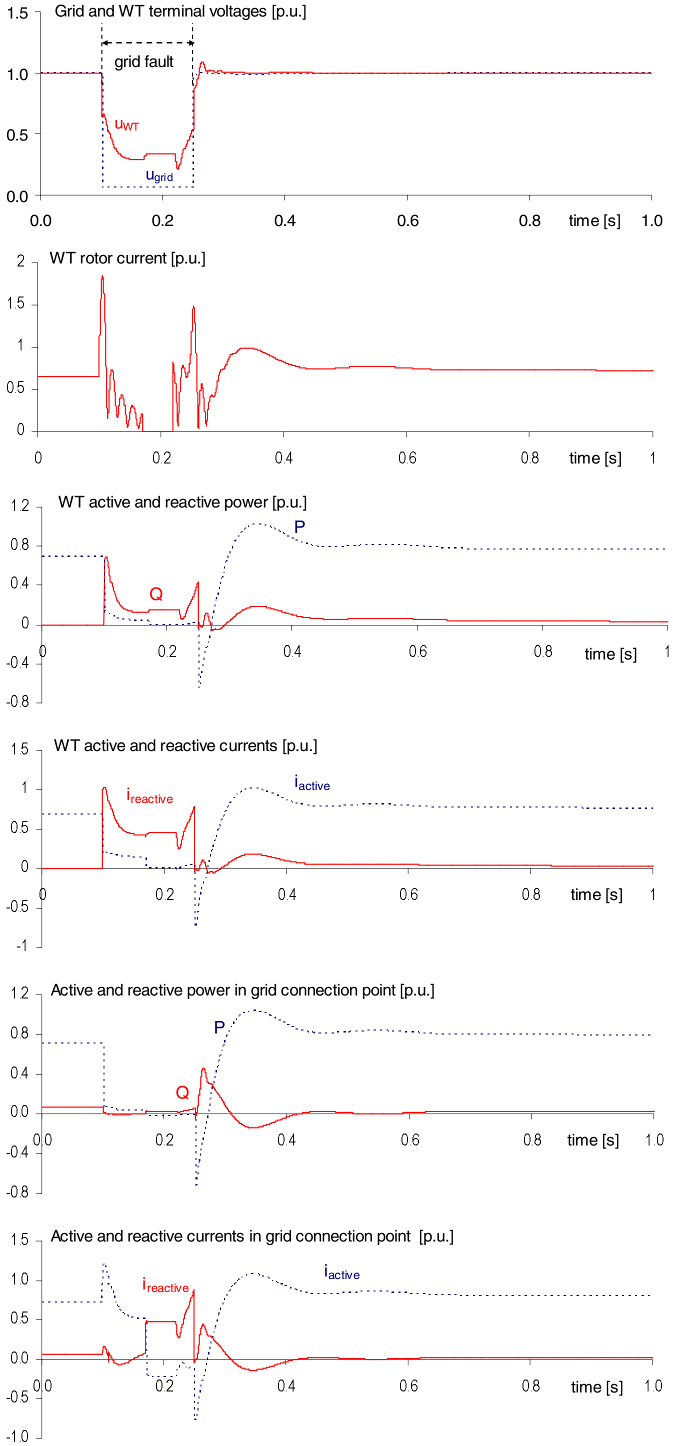

Fig. 17. Dynamic response of the offshore wind farm to three-phase grid short circuit

The voltage dip experienced by the WT is much less than that in the grid. This is due to the considerable impedance between both nodes. Moreover, the WT control is extended to provide a strong voltage support. In particular, this is realized by the rotor side converter as long as it remains connected to the rotor circuit. In addition, the line side converter is controlled for forced reactive current generation considering a temporary overload of the converter bridge. As a result the WT terminal voltage remains at about 65%, which may not lead to compulsory crowbar firing. However, in this simulation the crowbar has been activated. During the fault the active power supplied to the grid is small as the result of the low voltage profile. However, active power in-feed is not needed by the power system in this stage because of the fact that the load is also small, but reactive current is needed to support the voltage. In the initial phase extending to about 20 ms, the WT discharges the magnetic energy so that the reactive current achieves its first peak of about 1.0 p.u. But this current decays quickly. Due to the fact that the crowbar is activated, the DFIG becomes also a reactive power consumer. However, since the line side converter also supplies reactive current the WT as a whole remains a reactive current generator. On the grid side a considerable reactive current is observed first when the WT active power in-feed goes to zero. It should be noted that the active current transmission adversely affects the grid voltage support during faults. During the time period when the rotor and converter are disconnected and the crowbar is switched off the power generation becomes zero for physical reasons. As can be seen from the simulation results the wind farm is able to supply about 50% reactive current during this stage. After voltage recovery the WT control brings back the voltage very fast near the reference value without considerable oscillations.

VII. CONCLUSION

Wind power is one of the major emerging technologies in the power area. In the last decades, the size of wind turbines and wind farms increased rapidly. Therefore, the integration of wind power into the power system needs particular attention to ensure grid-conform behaviour. FRT and reactive power generation are the major concerns that have to be addressed by the manufacturer before grid connection is approved by the utilities. Modern wind turbines utilize voltage source converter technologies for adapting rotor shaft speed to the wind speed. However, due to the power electronic components wind turbines are sensitive to overloads.

In the future further research is needed to identify new or improved approaches for enhancing the interactive behaviour of wind turbines and power systems. Wind turbines differ from conventional generators, but they also open up some new possibilities that can help run future power system more reliably and safely.

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IX. BIOGRAPHIES

Istvan Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modelling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE.

Heiner Brakelmann studied electrical engineering at the Technical University of Aachen (diploma in 1971), where he wrote his doctoral thesis about circuit-breakers in 1973. In the following years, he was with the Felten & Guilleaume Energietechnik AG in Cologne as leader of an R&D-group, engaged in power cable problems. In 1977 he started as chief engineer at the University of Duisburg, got his habilitation in 1985 and became a full professor in 1994. He is member of CIGRE SC 21 (Cables) and of CIGRE-WG B1-05 („Transient effecting long cables“). He is the author of more than 130 technical publications and of three book-publications in the field of cable technique as well as high-voltage and high-current problems.