Dynamic Behavior of Offshore Wind Farms with AC Grid Connection

I. Erlich, *Senior Member, IEEE*, S. Bopp, W. Winter

Abstract— **This paper surveys various issues of interest pertaining to the dynamic interaction of large offshore wind farms with the grid. The requirements on wind generation plants for interconnection to the grid as they relate to the German grid code have been elaborated, and technical features of modern wind turbines with respect to their capability to meet these requirements discussed. Today, modeling and simulation remain the only possibility to gain insight into the interaction of large offshore wind farms with the grid. Accordingly, following the introduction and discussion of selected wind turbine models, the dynamic behavior of wind turbines based on doubly-fed induction generators (DFIG) in a representative wind farm connected to the grid via AC cables has been exemplarily illustrated. The results demonstrate that fault ride-through even down to zero voltage is possible, while voltage support by wind farms at the Point of Common Coupling (PCC) is limited due to the typical length of the link between proposed off-shore wind farms and the grid.**

I. INTRODUCTION

THE transient stability of conventional power plants consisting of synchronous generators is a well known phenomena and corresponding investigations are carried out as a matter of routine by grid operators. Often the term transient stability is considered to be synonym for all dynamic phenomena dominated by synchronous generators.

In the foreseeable future wind farms with hundreds or even thousands of megawatts installed capacity will be built offshore. Such wind power plants are usually connected to the grid through long submarine cables which are designed to carry the maximum power without considerable reserve capacity. Without proper planning, the long transit route in conjunction with heavy loading of transmission cables make the offshore wind farms susceptible to dynamic problems. On the other hand modern wind turbines are controlled by power electronic converters and thus they provide some unconventional methods for stabilizing wind farms following grid faults. The response time and characteristic behavior of wind turbines differ considerably from that of conventional units. Accordingly further research and investigations are necessary to understand the characteristic dynamic phenomena underlying wind turbines in interaction with the grid. On the other hand dynamic models suitable for large scale dynamic studies are rarely available. Important details of wind turbines and corresponding converter controls are usually confidential due to the market relevance of innovations continuously introduced by wind turbine manufacturer.

German grid operators are requiring dynamic studies before approving grid connection. The investigations are usually carried out with wind farms represented in detail and with the grid modeled as an infinite bus. In the future German grid operators are planning to carry out comprehensive studies on interaction of wind farms with the grid, for which, however, suitable models are required.

The present paper will discuss different issues related to wind farm dynamic behavior. First, grid code requirements, which have to be fulfilled by wind farms, are introduced. Then wind turbines and corresponding control concepts will be discussed followed by an overview of the current situation regarding wind turbine modeling. This will be followed by simulation results for a typical wind farm composed of 17 DFIG wind turbines each with 3.5 MW rating. Finally, the behavior of wind turbines with respect to their impact on the grid is discussed followed by conclusions and an outlook concerning future developments.

II. GRID REQUIREMENTS

In figure 1 the typical configuration of offshore wind farms is shown. The wind farm is connected to the grid (Point of Common Coupling, PCC) through AC cable. A typical nominal voltage used today is 110 kV or 150 kV, but there are new developments in submarine cable technologies permitting a voltage of up to 240 kV. The cable is compensated on both ends by shunt reactors which can only be switched together with the cable. The reactors are designed in such a way that a portion of the cable's charging reactive power remains uncompensated (10-30%) and therefore, through normally only marginal, can nevertheless be used as a source of reactive power supply to the grid. The reactors can also be controlled continuously in the range of 40-100% of their ratings. For practical reasons it is sometimes recommended to install a fixed reactor offshore and a controllable reactor (which is a more complex equipment) on the land side for increased flexibility. The wind turbines within the wind farm are linked to one another using medium voltage cables (20 kV, 33 kV) which usually have a radial structure. The step up transformer placed on the platform caters for voltage control in the medium voltage grid. The transformer at the onshore end of the cable maintains the transmission voltage level always high to reduce transmission losses. Transformer tap changers, shunt reactors together with the wind turbines themselves constitute

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the voltage and reactive power control options to meet grid requirements at the PCC. However, voltage control within the short timeframe for dynamic response can only be provided by the wind turbines.

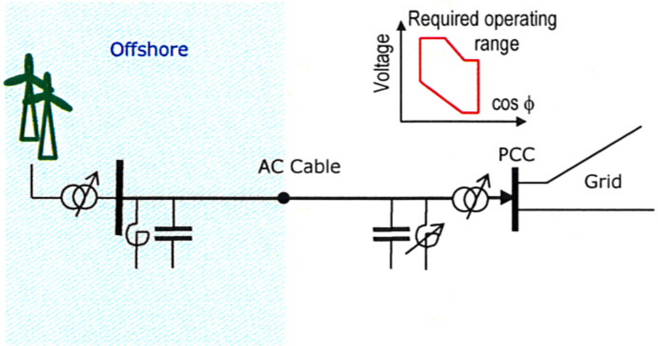

Fig. 1 Typical wind farm configuration

The major grid code requirements [1], [2] relating to wind turbine behavior following grid faults concern fault ride-through (FRT) capability and voltage support during fault. Special requirements necessary to ensure conformity of offshore wind parks and the connection system are introduced by the system operator E.ON Netz in [3]. Based on the existing Grid Code, slight modifications are included in the special requirements for offshore grid connections to take into account of the special characteristics of offshore connections.

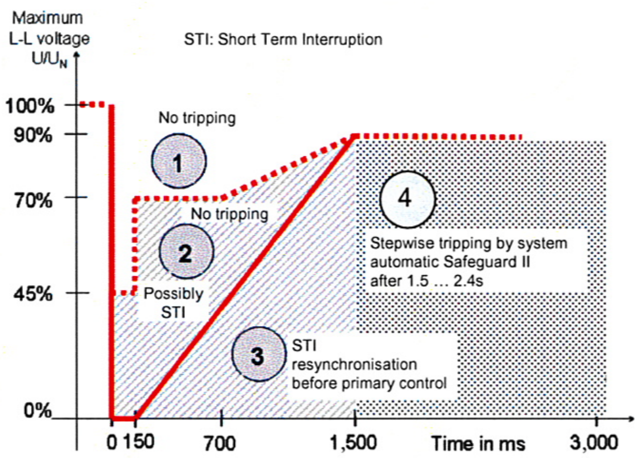

Fig. 2 German FRT requirements

The German FRT requirements are summarized in figure 2. In general, separation from the grid is allowed only as a Safeguard which represents system protection schemes. In case the local voltage at PCC remains low despite voltage recovery elsewhere in the grid and wind turbines fail to provide any voltage support as required, the Safeguard initiates separation of wind turbines in three steps starting from 1.5 s after the fault. Up until this point wind turbines have to stay connected even if the voltage at PCC drops down to zero. However, at very low voltages, about 10-20%, most wind turbines will stop the operation of the converter for protection against high currents. Normally the converter is started again after 5-10 ms, although it may remain deactivated during the whole fault period under certain circumstances. The grid code considers such technical limitations of converters by allowing Short Term Interruptions (STI) in areas 2 and 3 as shown in figure 2.

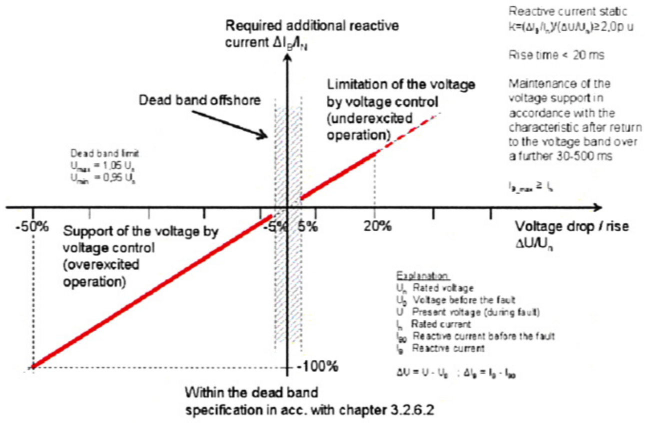

Fig. 3 Voltage control characteristic for offshore connections. In certain cases, the gradient of the voltage support can differ.

Voltage control during the low voltage period is generally required. Figure 3 shows the control characteristic defined in the special requirements for offshore grid connections. It represents a proportional controller. Even though voltage support has to be provided to the PCC the controller is realized as a local one due to the fast time characteristic required. The impact of voltage support by offshore wind farms suffers from the long distance that may reduce the effect on PCC considerably.

III. Technical Capabilities of Wind Turbines

The development of modern wind turbines is characterized by two main directions. One type of wind turbines uses the DFIG where the converter is located on the rotor side and dimensioned for a capacity of about 20-30% of the nominal power. The second type is based on synchronous generators which are connected to the grid through a full-size converter. The basic structures and control options are shown in figures 4 and 5, respectively.

Wind turbines based on DFIG face high rotor currents during fault. Especially the first peak may exceed the limitation of IGBT valves [4] calling for stop of control action. Nevertheless, the energy continues to flow to the DC link through the diodes raising the DC voltage in the process. As a first option for limiting the voltage the DC chopper is switched on. If the chopper is unable to limit the voltage increase due to the large energy mismatch, the crowbar, which basically is a three phase resistance, will be switched in to the rotor circuit. The crowbar remains switched on for 50-100 ms and it takes in all about 100-150 ms until the converter resumes supplying the rotor circuits again. During this time the wind turbine resorts to reactive power consumption. For grid code compliance crowbar firing is not the desired option. Recent development shows that crowbar action can be precluded in most cases by using DC chopper with higher capacity. Even if the IGBT are stopped as a result of high currents it takes not longer than a few ms until the wind turbine becomes controllable again since the DC voltage is limited by the chopper.

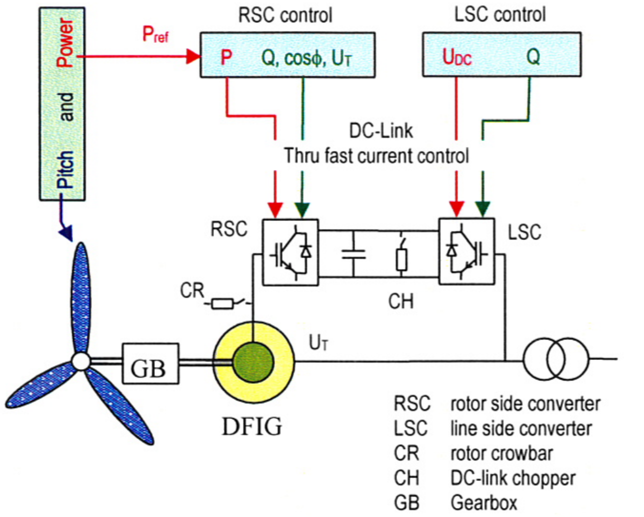

Fig. 4 Wind turbines with Doubly-Fed Induction Generators

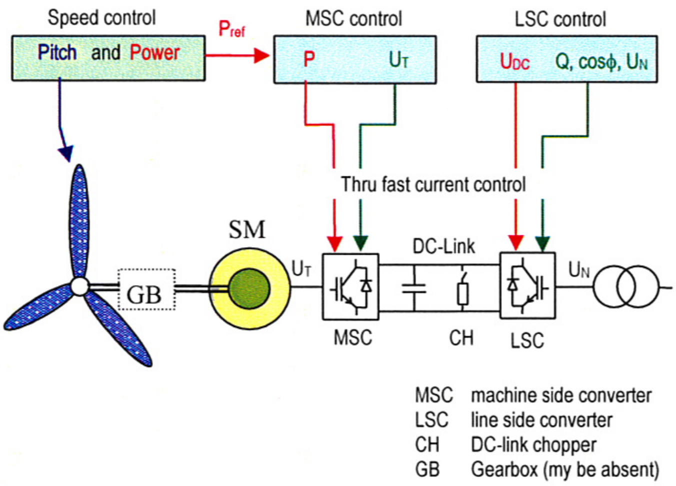

Fig. 5 Wind turbines with Synchronous Generators and full-size converter

For reactive current injection, the DFIG provides two alternatives, namely through the Machine Side Converter (MSC) and the Line Side Converter (LSC). The MSC is more suitable on account of the amplifying effect of the DFIG. The LSC has to control active current as a priority, but when there is current capacity margin the LSC can also be used for producing reactive current. The LSC acts faster than the MSC. As a result, the LSC provides a valuable contribution immediately following the voltage drop.

Wind turbines with full-size converter supply the total power through the converter. In the event of voltage dips in the grid the LSC switches to reactive current priority with the consequence that the active current injection may be reduced. However, constrained by the need to avoid undesirable acceleration the MSC can not always reduce the active power adequately. The difference will lead to increased DC voltage. The only option for keeping the voltage within limits is the DC chopper that has to absorb the surplus power. Braking resistors connected to the stator are switched on when the speed attains undesirable values. Full-size converter systems respond faster to grid disturbance, but are more sensitive to changes in grid voltage magnitudes and phase angles than DFIG based wind turbines. In case of very low voltages or sudden changes of voltage phase angles the LSC will stop like the DFIG based systems. However, if the conditions for secure operation are fulfilled the converter will synchronize again even if the voltage is still low. Reactive current injection and thus voltage support with full-size converter system is possible within the maximum current limitation. That means the reactive current can be increased at the expense of active current injection, in a manner similar to the DFIG based systems.

IV. Modeling Issues

Manufacturers are using comprehensive simulation models for testing wind turbines and the associated converter systems. However, for grid studies such models are not suitable because of the high computational effort required for simulating such large power systems. For dynamic simulation of power system usually reduced order models that use complex algebraic equations for the grid including the stator circuits of electrical machines are employed. Differential equations are only used for the rotor including the equation of motion and the converter control system. In consequence large power systems can be simulated within acceptable time frames, but the results obtained represent only the RMS values. On the other hand wind turbine converter control systems evaluate instantaneous voltages and currents.

In DFIG systems, the stress on the MSC is to a large extent caused by the DC component that may exist in the rotor current following grid short circuits. But DC current components cannot be captured by using reduced order stability type models. This problem is still not satisfactorily solved. A tentative approach for model extension is presented in [4], [5] and will also be used in the simulation examples presented in this paper.

The second impediment one may face while developing accurate wind turbine models is the confidentiality issue. Some manufactures are unwilling to give away detailed information to avoid their competitors getting hold of them. Standard wind turbine models are currently under development, but not all phenomena are covered by these models. As an example figure 6 shows the MSC controller of DFIG systems. Inputs are the active and reactive wind turbine power references. The active power reference is supplied by the speed controller which is a separate unit not presented here. The reactive power reference is set according to the grid requirements. The voltage controller adds up a signal to the reactive current reference, which, however, is zero as long as the voltage remains within the tolerance range. The magnitude of current reference is limited, but different strategies can be applied to determine which component is to be reduced first. Active current priority is the standard in normal operation mode, which means that the active current is not reduced as long as the current magnitude can be kept within the limit by reducing the reactive current reference only. Reactive current priority is applied during low voltage period when voltage support is required by the grid. Treating active and reactive currents equally is also a possibility. The rotor current controller calculates the exact rotor voltage that results in the desired rotor current reference in steady state. The equations represented in this part are developed from the DFIG equations. More detailed description of DFIG wind turbine model can be found in [4]-[6].

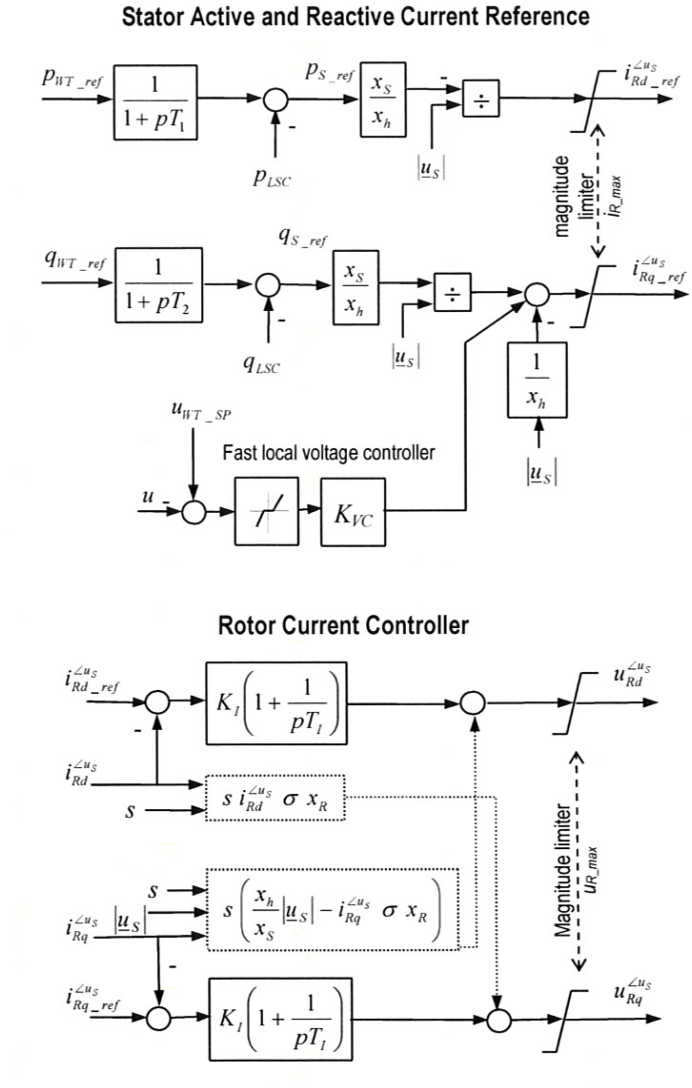

Fig. 5 Model of DFIG MSC controller

V. Grid Example

The objective of this study is to show typical wind farm behavior following three phase grid faults and then, on the basis of the simulation results, to verify and/or assess the limits of grid code compliance. For this purpose, a generic offshore wind farm shown in figure 7 has been used. It is composed of 17 DFIG, each with a rating of 3.5 MW. The wind farm does not directly reproduce any particular existing or planned wind farm. Neither do the individual wind turbine units necessarily correspond to any of the existing wind turbine types. However, both the configuration of the wind farm and the parameters are chosen judiciously to reflect typical wind farm scenarios.

The model used encompasses all the essential components of DFIG and the associated control systems that are of significance following three phase grid faults. Wind turbine simulations are characterized by small integration time steps of around 1 ms. Small steps are necessary for considering protection actions like switching of chopper, crowbar or even blocking of the whole converter.The models used allow simulation of voltage dips up to zero voltage although the simulation remains a stability type, one based on RMS values.

The wind farm is represented in detail up to the level of individual wind turbines. Faults are included on the grid side behind an impedance to be used to control the severity of voltage dip. Only three phase short circuits are simulated in this study. All wind turbines are assumed with initial nominal power and power factor of 1.0 at the medium voltage side of the wind turbine transformer.

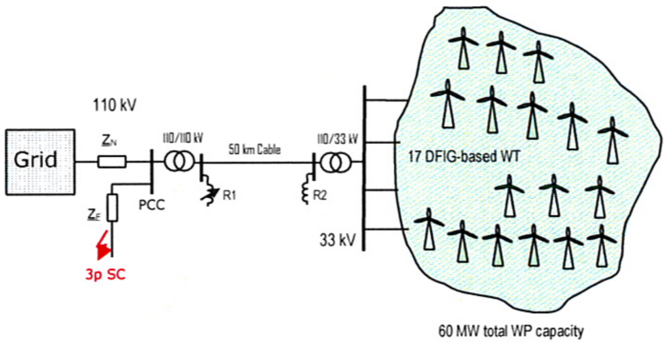

Fig. 7 Test wind farm

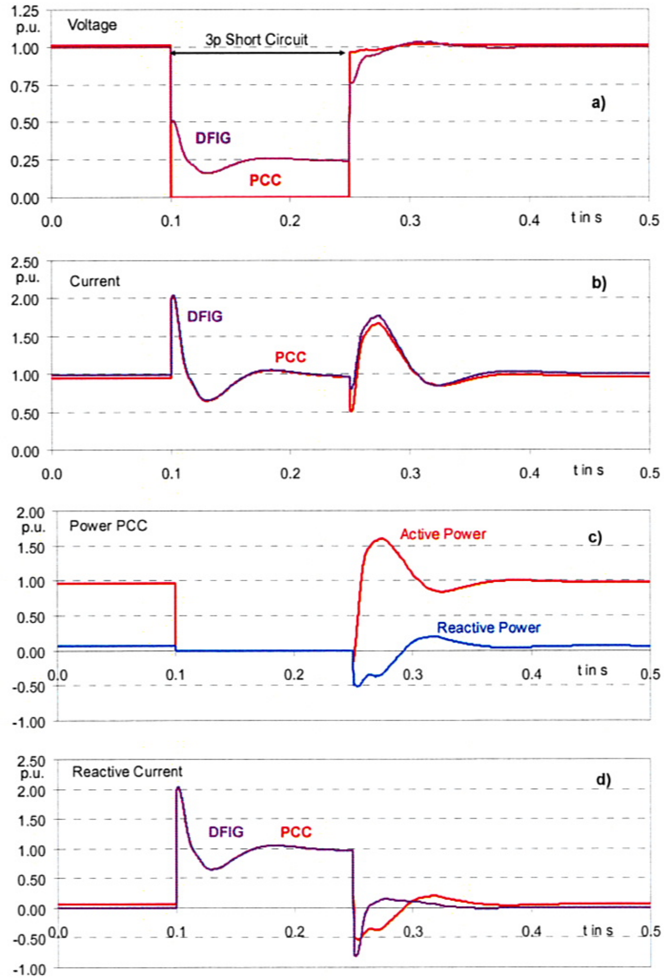

Fig. 8 Response of wind farm to zero voltage dip at PCC

As a first example, a fault leading to zero voltage at the PCC has been simulated. Figure 8 shows the response of DFIG based wind turbines.

Despite zero voltage at PCC wind turbines continue running in normal operating mode and supply reactive current according to grid code requirements. As result the voltage at the wind turbine terminal remains at about 0.25 p.u. For the duration of the zero voltage period, synchronism with the grid is lost. Although the grid voltage recovers with an indeterminate phase position wind turbine control negotiates a new steady state operating point within 200 ms. The DFIG based wind turbines supply a short circuit current of about 2.0 p.u. which represents the AC component only. However, the short circuit current decays faster than the case in conventional synchronous machines due to the typical parameters of the induction machine on the one hand and the forced converter current control on the other.

Figure 9 shows the response of wind farm to 10% PCC voltage fault.

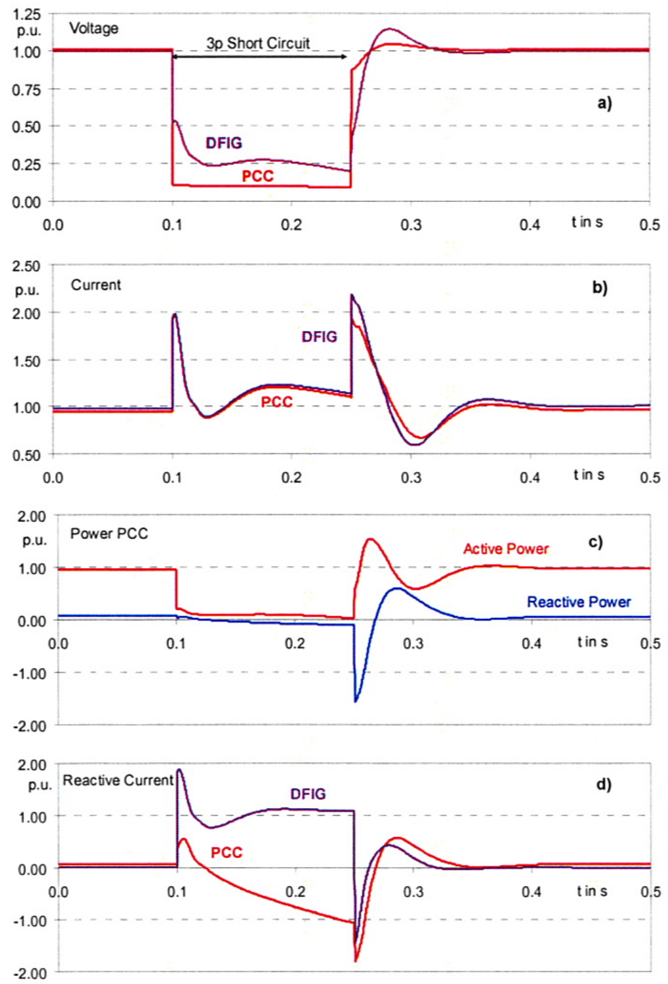

Fig. 9 Response of wind farm to 10% voltage dip at PCC

Considerable difference to the zero voltage fault concerns the reactive current supplied into the PCC as shown in figure 9d. After approximately 20 ms the wind farm behaves as a reactive power consumer, despite the fact that wind turbines are supplying about 1.15 p.u. reactive current. It seems that in this case due to the electrical relationships and the residual voltage at PCC it is physically not possible to provide a real reactive current contribution by the wind farm.

Figure 10 shows the response of wind farm to 50% voltage dip at PCC. The difference between PCC and wind turbine voltage is about 20 %. Therefore, the injected reactive current by the wind turbines is less than what is provided for by the grid code as shown in figure 3. Due to the reactive losses along the transmission line the reactive current into the PCC is about 0.3 p.u., which is far below expectation.

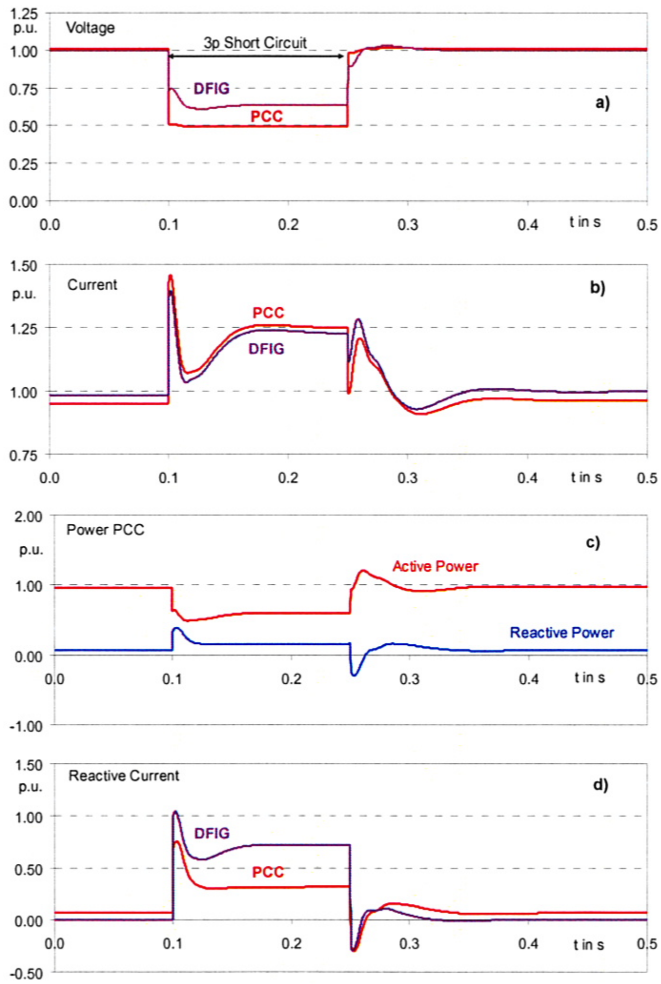

Fig. 10 Response of wind farm to 50% voltage dip at PCC

It is obvious that voltage support to PCC by offshore wind farms connected to the grid through long cables is limited. Some improvement can be achieved with higher voltage controller gain. In these cases, the special requirements for offshore grid connections [3] stipulate that the gradient of the voltage support can be increased.. However, the voltage support is always limited by the maximum allowable converter current.

In the first 10-30 ms following the voltage dip DFIG based wind turbines supply reactive current into the grid on physical grounds due to the reduction of magnetic field. However this phenomenon decays fast and the reactive current initiated by the MSC control needs time to pass through the induction machine system. During this time the LSC can assist as a back up in terms of reactive current generation. After voltage recovery the magnetic field within the DFIG has to be restored. Therefore, the machine behaves for a short period as a reactive power consumer reminiscent of the behavior of the conventional SG.

Some severe disturbance may lead to blockage of converters for protection reasons. The example shown in figure 11 has been calculated with 8 wind turbines only. i.e. 9 turbines are switched off. Zero voltage fault will result in this case in stopping of LSC and MSC for the whole fault period. It is obvious that 8 wind turbine cannot keep the wind farm voltage high enough for secure normal mode operation. The voltage drops below 15% which has been implemented in the model as the deepest value allowed. After voltage recovery the converter starts again immediately and the active power is increased according to a predefined ramp within 150-200 ms. For the grid such a short term interruption following very low PCC voltage dips is acceptable provided that the restart proceeds without any delay and completed within a few hundred milliseconds.

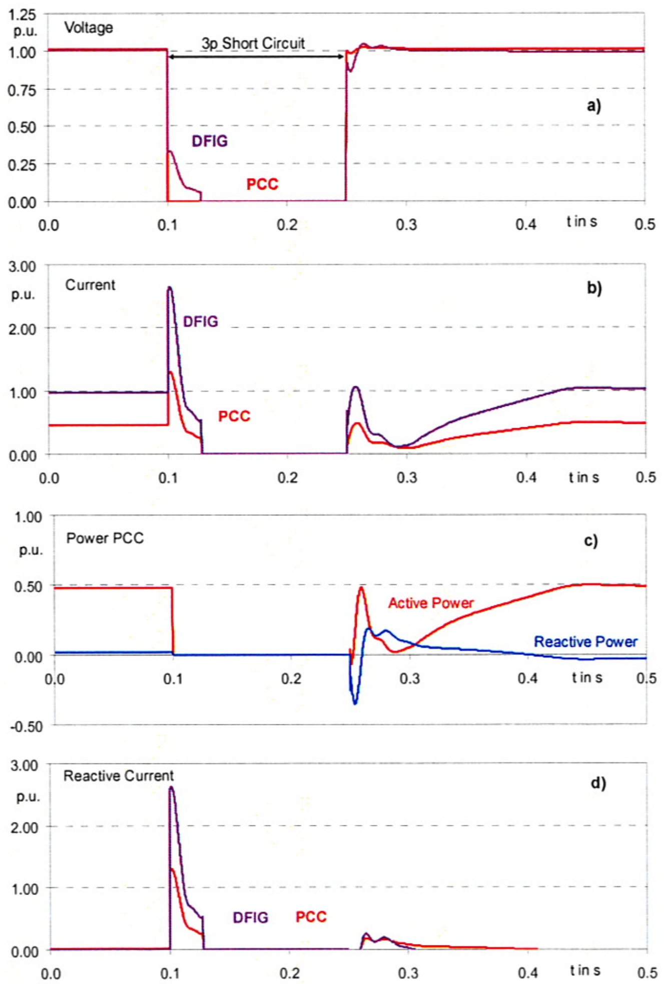

Fig. 11 Response of wind farm to zero voltage dip at PCC. Only 9 turbines from the installed 17 are running with nominal power

VI. Conclusions

The behavior of modern wind turbines following grid faults is substantially affected by the converter and corresponding control. Moreover the dynamic response is much faster than that of conventional synchronous generators. On the other hand the overloading capability of wind turbines is limited due to the semiconductor devices employed. Therefore, following severe disturbances converter may stop for a short period which results in a short interruption of supply. During the low voltage period wind turbines have preferentially to inject reactive current into the grid. Active current plays a secondary role and can be reduced simultaneously. However, due to the possibly of long distance between wind farm and grid the effect of reactive current injection by wind turbines on the PCC voltage is limited.

DFIG based wind turbines provide additional support during the first 10-30 ms following short circuits by discharging the magnetic field energy. Simultaneous coordinated control of MSC and LSC enables DFIG systems to supply reactive current according to grid code requirements during low voltage periods. Wind turbines with full-size converter generate the full amount of reactive current required by the LSC and react more quickly. However, sudden changes of voltage magnitude or phase angle may result in short interruption of converter control, which on the other hand, does not adversely affect grid security.

Compared to classical synchronous generators wind turbines behavior is not characterized by electromechanical rotor oscillations. The transient process is almost entirely dominated by converter control which causes a virtual decoupling between generator and grid.

For the German grid operators and the relevant experts to quantify wind farm's behavior on the grid, detailed simulation studies are necessary. However, there is still a lack of appropriate models that can be used. In the future, further effort is required to either define standard wind turbine models or manufactures to provide detailed models to the necessary party. Besides, manufacturers have to verify these models and provide corresponding parameters.

VII. References

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VIII. 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 IEEE.

Wilhelm Winter received the M.Sc. degree and the Doctor degree in Power Engineering from the Technical University of Berlin in 1995 and 1998 respectively. From 1995 to 2000 he was with Siemens, working in the department for protection development and in the system planning department. He was involved in large system studies including stability calculations, HVDC and FACTS optimizations, Modal Analysis, transient phenomena, real-time simulation and renewable energy systems. .He was responsible for the development of the NETOMAC Eigenvalue Analysis program. Since 2000 he has been working at E.ON Netz, responsible for system studies, system dynamics and the integration of large scaled wind power.

Siew Bopp received the B.Eng (Hons) and PhD in Electrical and Electronic Engineering from the University of Manchester Institute of Science and Technology (UMIST), UK in 1999 and 2002 respectively. During her postgraduate studies, she was a research associate with EA Technology in the development of ancillary services in distribution systems. In 2002, she joined EDF Energy, UK as a strategic network development engineer, responsible for the development of the East of England distribution network as well as technical, commercial and regulatory strategy on the integration of distributed generations. Since 2003, she is a Network Planning Engineer in E.ON Netz GmbH, Germany, responsible for technical and planning aspects in the grid connection of large offshore wind power.