Response of DFG-based Wind Farms Operating on Weak Grids to Voltage Sags

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Abstract — The integration of wind power into the electrical power systems is continuously increasing all over the world. In many power systems the wind resources are located in remote areas far away from the load centres. Then the short circuit ratio (SCR) at the point of common coupling (PCC) could be small and needs special consideration in wind turbine control and operation. In this paper the authors investigate the effect of the SCR on the behaviour of wind farm following sudden voltage drop due to grid short circuits. For this a 90 MW wind farm has been simulated taking into account realistic DFG and corresponding controller implementations. The objective of this paper is to provide an insight in to the capability of DFG-based wind farm to participate in voltage support during grid faults especially in weak power systems.

***Index Terms* — Wind Power, grid integration, doubly fed generator, fault ride through, voltage support, weak power system**

I. INTRODUCTION

The trend in wind generation in the whole world has been the installation of large and concentrated wind farms including expected offshore wind farms into the electrical power systems. Large-scale generation units were connected to distant load centres using long transmission lines. Besides the geographical distance between generation and load in some regions especially in Europe the wind energy injection is already exceeding the local demand. Both aspects underline that wind energy has reached significant penetration levels. These issues cause numerous technical challenges for a successful integration of wind power into especially weak power systems. Due to the coming grid integration of more and more renewable energies all over the world it is expected that the short circuit power of power systems will decrease.

State of the art wind turbines are equipped with self-commutated power electronic devices to adjust active and reactive power of the generator independently without additional compensation devices. It can be distinguished between two basic concepts regarding the electrical generator unit of wind turbines. On the one hand there is the full converter concept in which the generator is connected to the grid through a full-scale converter system. The full-scale concept can be used with asynchronous as well as synchronous generators. On the other hand most of the currently installed wind turbines are equipped with the so called doubly fed generator.

Large wind generation units have capacities comparable to conventional power plants. As a consequence grid operators require them to participate in grid voltage support in steady state as well as during faults. Many grid codes all over the world contain dynamic requirements like the fault ride through (FRT) ability of generating units. Additionally voltage support during grid faults due to the injection of short time reactive current is requested in certain grid codes. The gain factor for the injected reactive current can vary according to the voltage support characteristic of the grid code and the short circuit power at the PCC. FRT capability plus voltage support guarantee a secure operation of the power system even with high wind power generation due to minimizing the risk of losing a large amount of wind generators during faults.

Therefore the paper includes dynamic simulation results of DFG-based wind farm connected to a weak power system topology during grid disturbances. Chapter II gives an overview about the state of the art DFG configuration and control. Chapter III explains the actual German grid code requirements regarding the dynamic behaviour of generation units during grid disturbances. Chapter IV provides information about the used test topology. In Chapter V simulation results are visualized and compared. Chapter VI finally gives a conclusion.

II. DFG-BASED WIND TURBINE

A DFG-system can combine fast control due to the high switching frequency of the power electronics and moderate costs due to a partial rated converter system compared to the nominal power of the wind turbine. Figure 1 shows the basic concept of DFG based wind turbine, which uses a slip ring induction generator. The number of pole pairs varies between two and three. Therefore the slow speed of the wind turbine shaft has to be converted by a gear box. While the stator of the generator is directly connected to the grid, the rotor windings are linked to the grid through voltage source converters. These voltage source converters are usually equipped with Insulated Gate Bipolar Transistors (IGBT) and are using a standard three-phase bridge configuration. Both two-level power converters are coupled via a DC-link capacitor to a back-to-back system. The IGBTS are controlled by pulse width modulation signals from a digital signal processor. The rotor circuit and so the converter circuit can be dimensioned for 20

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up to 30 % of the nominal active power of the wind turbine.

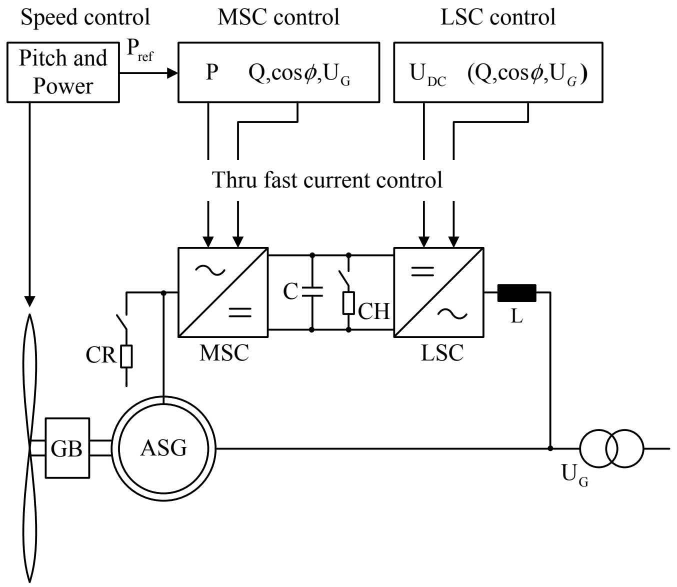

Fig. 1. Basic concept of DFG-based wind turbine

Basically the control of the DFG can be separated into the line side converter (LSC) and the machine side converter (MSC) controls. Both converters are based on a feed forward decoupled current control which allows an independent adjustment of active and reactive current. The theoretical background of modelling DFG systems and its control is already published in numerous papers, e.g. [1] and [2]. The main function of the LSC is to maintain the DC voltage and provide reactive current support for optimization of the reactive power sharing between MSC and LSC in steady state. During grid faults additional short-time reactive power has to be supplied to support the grid voltage. The LSC control is aligned to the grid voltage in the rotating reference frame. Figure 2 shows the inner current control loop of the LSC.

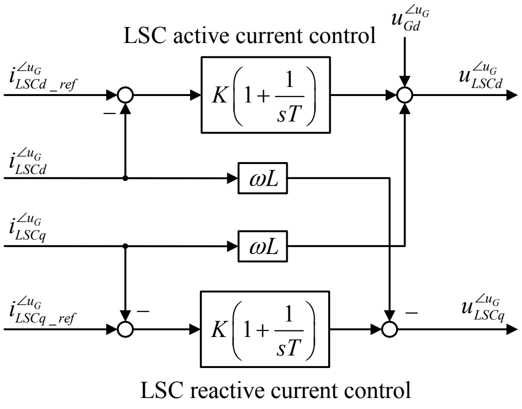

Fig. 2. LSC inner current control loop

The MSC controls active and reactive power of the DFG independently from one another and follows a tracking characteristic to adjust the generator speed for optimal power generation depending on the wind speed. The MSC control is aligned to the stator voltage in the rotating reference frame. Figure 3 shows the inner current control loop of the MSC. The MSC operates at slip frequency.

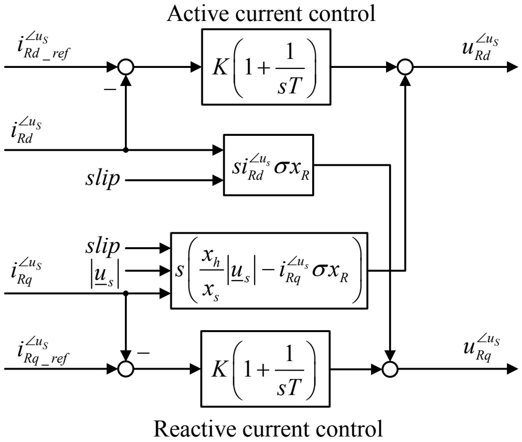

Fig. 3. MSC inner current control loop

The mechanical power generated by the wind turbine drives the DFG, which feeds electrical power into the main grid through the stator and the rotor windings. The converter allows controlling the amplitude, frequency and phase angle of the rotor voltage. This enables variable speed operation of the DFG, which can be used to adapt the generator speed according to the wind speed to increase the wind power utilization for a given wind turbine. The speed range of generator is about +/- 30% of the synchronous speed. Thus the speed of the generator is decoupled from grid frequency. The slip power is fed to the grid through the converter in supersynchronous operation or drawn from the grid in subsynchronous operation. In addition to the independent adjustment of active and reactive current and thus P and Q, the speed variability is an important property of modern generator concepts.

For protecting the components against overvoltages and overcurrents, additional components are necessary. This includes a DC-link chopper (CH) as well as a rotor crowbar (CR). The chopper protects the DC-link against excessive voltages following grid faults and the resulting high stator and rotor currents. The proper dimensioning of the chopper resistor allows maintaining the DC voltage within allowable limits. Switching the crowbar during grid faults converts the slip ring generator to a conventional (squirrel cage) slip-ring asynchronous generator. For the duration of the rotor winding's disconnection, the excitation has to be provided by the stator terminal. Due to the required voltage support during grid faults, protection by CR and thus disconnection of the rotor from the converter should be avoided to the extent possible.

Regarding the dynamic behavior during grid faults the DFG system has to provide additional short time reactive current. Figure 4 describes the voltage controller implemented for this task. The voltage reference is adapted slowly to the current voltage so that before a sudden voltage drop happens the reference and the current voltages always correspond with each other. The controller can be extended by a dead band to avoid unnecessary control actions. In steady state the required reactive current setting i_{q_sta} is provided by a separate controller not shown in detail in Fig. 4. The output of the voltage controller i_{q_dyn} is added to the reference value for the reactive current in steady state mode i_{q_sta} and is forwarded to the inner current control loop. The share between LSC and MSC regarding the dynamic reactive current injection depends on the configuration of the system. The parameter for the gain factor k and the dead band DB can be adjusted according to respective grid code requirements.

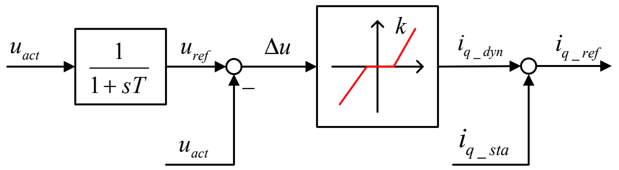

Fig. 4. Reactive current and voltage control schema

III. GERMAN GRID REQUIREMENTS

Due to the strong increase of renewable energy generation, especially the wind energy sector, in the last years new grid codes has to be published all over the world. For a reliable operation of the power system particular requirements concerning grid support during steady state operation and grid faults are formulated. According to these requirements state of the art wind turbines should not only stay connected to the grid during voltage dips. Additionally the reactive current control of the wind turbines must be used to support the grid voltage [3,4]. With modern protection devices the fault durations are normally in a range of some hundred milliseconds or less. The newest version of the German renewable energy law includes new regulations concerning ancillary services [5], which address this subject by specifying timing rules for the system response to grid faults. These rules are visualized on the diagrams in fig. 5 and fig. 6. Fig. 5 shows the voltage control characteristic that specifies the reactive current set-point depending on the depth of the voltage drop or increase. The controller may include a dead band of up to ±0.1 p.u. and has a setting range for the gain of 0...10 p.u. with a default value of 2 p.u.. To allow the controller also to react to small voltage deviations and to speed up the response a continuous voltage control can be favorable. The maximum available reactive current support of the generation unit for symmetrical faults is defined with 1 p.u.. Wind turbine must be able to supply at least 1 p.u. reactive current according to the proportional characteristic of the voltage controller.

Fig. 6 shows the timing requirements, which define a rise time of less than 30 ms and a settling time of less than 60 ms considering a tolerance band between +20 % and -10 % of the nominal current around the set-point. Both characteristics refer to the positive sequence quantities. It has already been proved [6] that DFG-based wind turbines can fulfil the sophisticated demands of the grid code requirements.

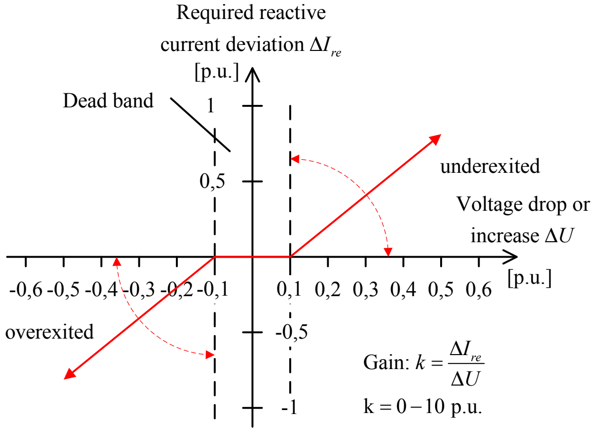

Fig. 5. Characteristic of voltage control

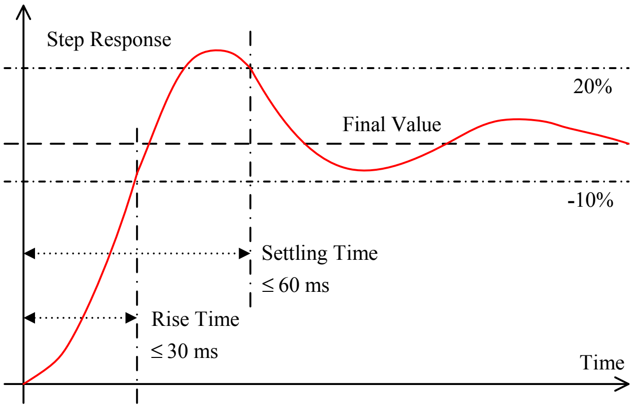

Fig. 6. Requirement for the timing of the injected current during grid faults

IV. TEST TOPOLOGY

In the test grid a 90 MW Wind Farm is modeled based on wind turbines which are equipped with doubly fed generators. The rated apparent power of the wind farm is 100 MVA. In the simulation environment one unit has the nominal active power of 6 MW, so the wind farm is equipped with 15 generators. The generation units are modeled as explained in Chapter II. The 33 kV medium voltage grid of the wind farm is a simplified network due to the fact that the impact of this underground cable or overhead transmission line based network is negligible. Three strings each equipped with five generators were summarized to one equivalent. The step up transformer from medium to high voltage has a rated impedance of 14 % which is a typical value for this kind of transformer. The wind farm is connected to the grid with a classical 110 kV AC overhead line of 50 km length. The parameters assumed are typical for such lines.

For the studies of a wind farm connected to a weak power system the point of common coupling (PCC) is defined at the busbar of the connected grid. Fig. 7 illustrates the configuration of the investigated power system. The ratio between short circuit power of the grid and nominal apparent power of the wind farm is called short circuit ratio (SCR) and was varied during the studies. The SCR was adjusted during the simulations in order the represent a weak and a relatively strong power system. In the case study for the connection to a weak power system a ratio of 4 was chosen which means that the short circuit power of the grid is 400 MVA. For the study of a strong power system the ratio was 20. This value implies that the short circuit power of the grid is 2000MVA.

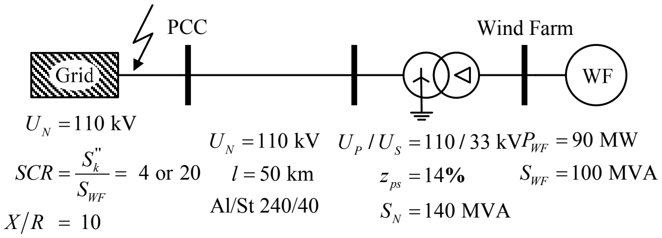

Fig. 7. Investigated power system with transmission line

During the simulations the wind farm was operating with a power factor of one in steady state. No further compensation devices were installed. A symmetrical short circuit at the bus bar of the grid led to a voltage sag of 55 % residual voltage with a duration of 200 ms at the PCC. Scenarios with different voltage controller gain were simulated and the effect of the voltage support of the wind farm during the grid disturbances at the PCC to the power system analyzed.

V. SIMULATION RESULTS

The results presented in the following chapter were simulated with Matlab/Simulink including the SimPowerSystems toolbox.

Fig. 8, 9 and 10 show the simulation results of the wind farm operating with nominal active power in steady state. The power factor is one and the farm is connected to a weak power system with a SCR of 4. The instantaneous values of current and voltage were measured at the medium voltage side of the HV/MV transformer. The active and reactive power curves are calculated with the instantaneous values of voltage and current and are represented in the consumer oriented reference system. The figures show that the wind farm although it is connected to a weak power system and additionally connected via a long transmission line can meet the demands of modern grid codes without facing stability problems. The wind farm provides reactive current and thus capacitive reactive power during a symmetrical grid fault with a very fast time response. The active power is ramped up after the voltage recovery in an appropriate time. The gain factor for the dynamic reactive current injection was chosen with 2 for this simulation. Without the voltage support of the wind farm the voltage level at the medium side of the transformer would drop to approximately 55% remaining voltage.

The effect of the voltage support can be compared in the following figures 11 – 18. The four figures on the left side represent the voltage level at the PCC while the wind farm is connected to the weak power system. The voltage level at the PCC in steady state mode is already reduced to an acceptable value of 95 % due to the fact that the Thevenin equivalent of the modeled voltage source has a significant voltage drop over the internal resistance. In order to get comparable results additional compensation devices were not used for this study.

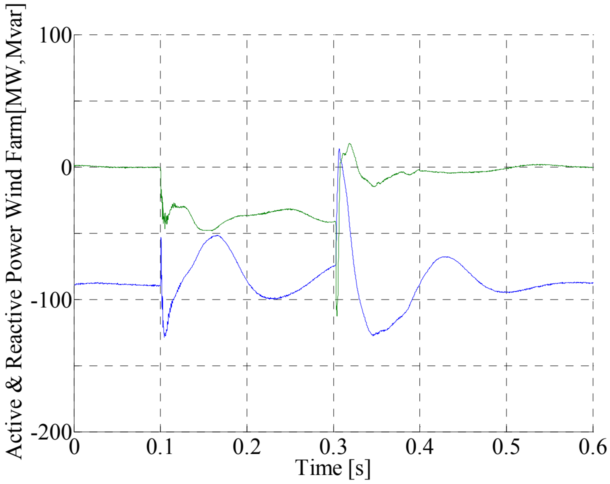

Fig. 8. Active and reactive power at the 90 MW wind farm during symmetrical grid disturbances connected to a power system with a SCR of 4

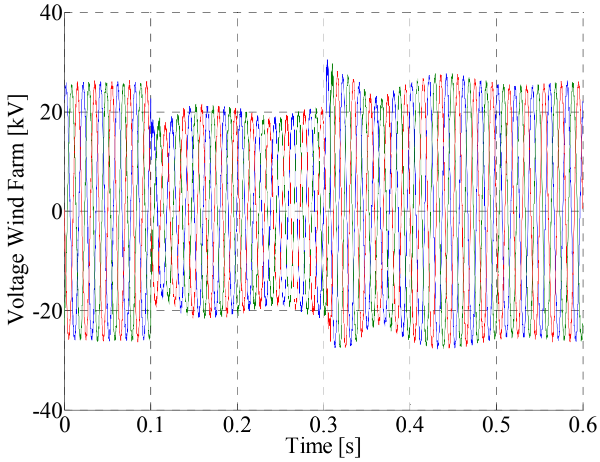

Fig. 9. Instantaneous values of the voltage (line to ground) at the wind farm connected to a power system with a SCR of 4 at the medium voltage terminal of the HV/MV transformer

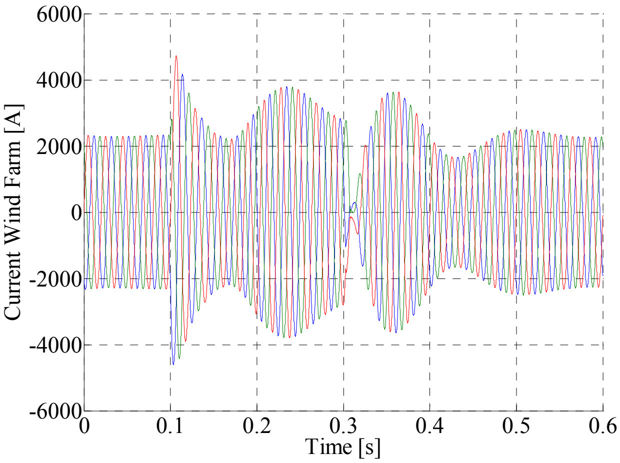

Fig. 10. Instantaneous values of the current supplied by the wind farm connected to a power system with a SCR of 4 at the medium voltage terminal of the HV/MV transformer

The four figures on the right side visualize the results for the wind farm connected to relatively strong power system. The voltage level in steady state is approximately one. The wind farm is operating with nominal active power in both scenarios.

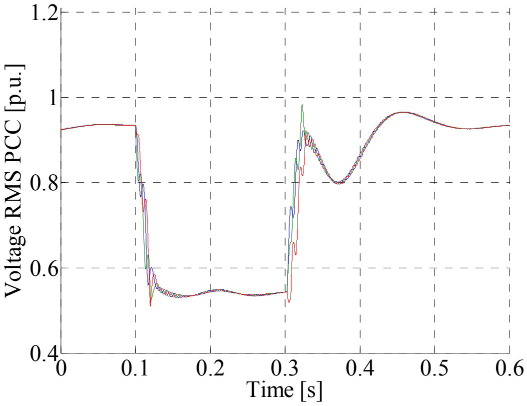

Fig. 11. Voltage level at the PCC, SCR = 4, reactive current gain = 0

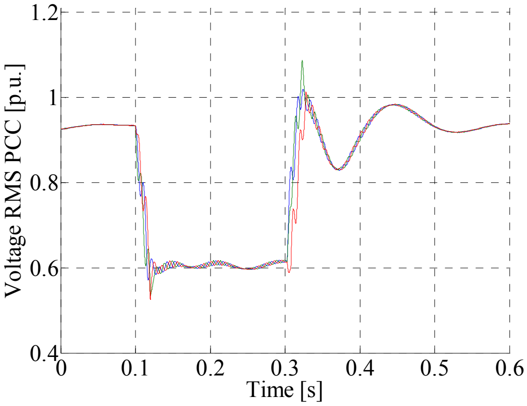

Fig. 12. Voltage level at the PCC, SCR = 4, reactive current gain = 2

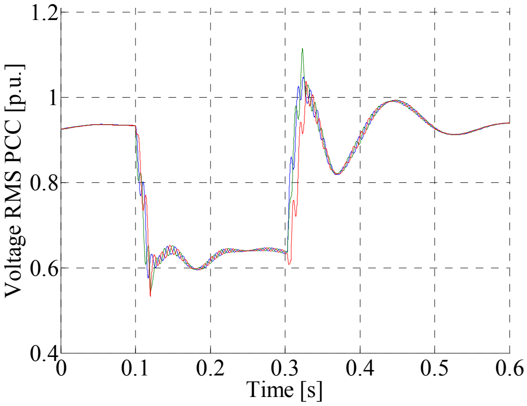

Fig. 13. Voltage level at the PCC, SCR = 4, reactive current gain = 5

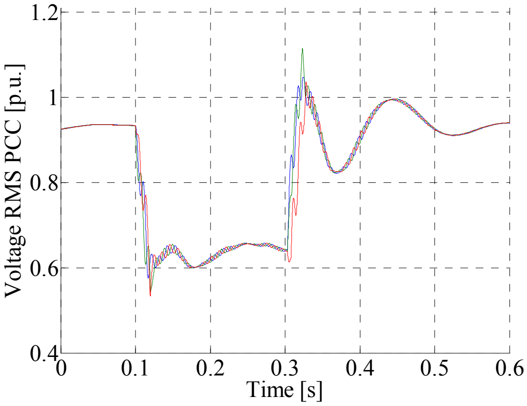

Fig. 14. Voltage level at the PCC, SCR = 4, reactive current gain = 10

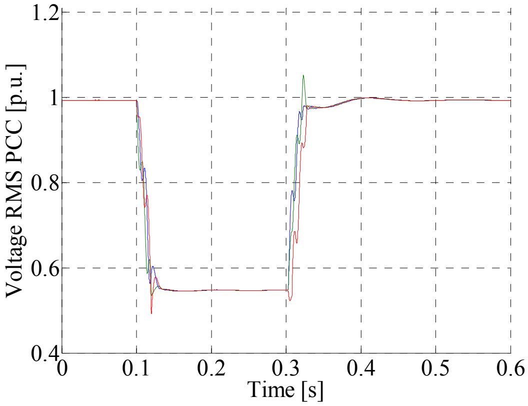

Fig. 15. Voltage level at the PCC, SCR = 20, reactive current gain = 0

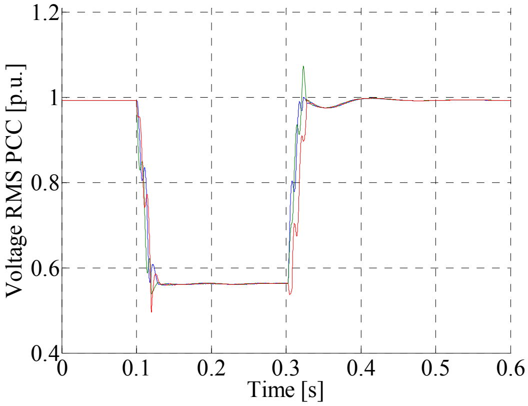

Fig. 16. Voltage level at the PCC, SCR = 20, reactive current gain = 2

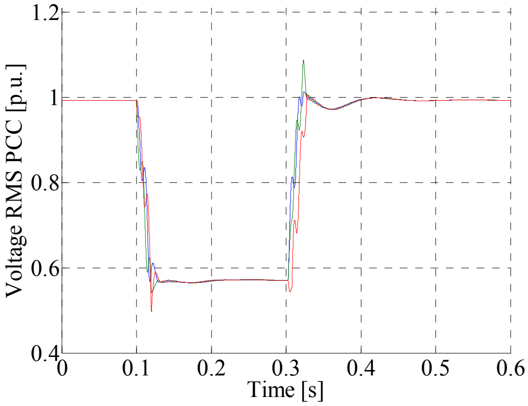

Fig. 17. Voltage level at the PCC, SCR = 20, reactive current gain = 5

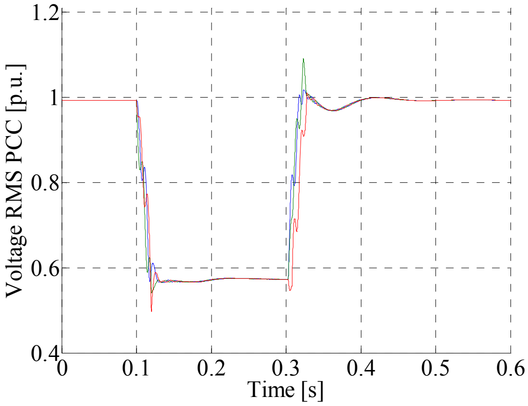

Fig. 18. Voltage level at the PCC, SCR = 20, reactive current gain = 10

The grid fault leads in both topologies to comparable voltage sags without additional reactive current. Regarding the voltage level at the PCC of the weak power system the injected reactive current of the wind farm results in a considerable voltage increase. Table 1 summarizes the different voltage increases for different gains. Due to the reactive current limitation to 1 p.u. the difference between gain factor 5 and 10 is not as large as expected. The voltage swings following voltage recovery can causes problems if the grid has a still smaller short circuit power. For this case study the damping of the oscillations is quite acceptable. Regarding the voltage level at the PCC of the strong power system the voltage support of the wind farm has a negligible effect on the voltage level at PCC. Only 2 % voltage increase can be realized with the maximum gain factor of 10 p.u..

TABLE I
IMPACT OF THE VOLTAGE LEVEL AT THE PCC

Gain factor [p.u.]	**Voltage increase at the PCC during a voltage drop to 55 % remaining voltage without support**	
	Voltage level, SCR = 4 [p.u.]	***Voltage level, SCR = 20 [p.u.]***
0	0.55	0.55
2	0.61	0.56
5	0.63	0.57
10	0.64	0.57

In further simulations a SCR of 3 and 2 was investigated. In these case studies the weak grid leads already in steady state operation mode to a significant voltage drop of at least 15 % at the PCC. As a consequence additional compensation devices (e.g. Statcom) would be necessary. For the comparability of the simulation results only a configuration without compensation devices at the PCC was part of these studies.

VI. CONCLUSION

Due to the decoupled adjustment of active and reactive power modern wind turbines are able to participate in voltage control of power systems in steady state as well as during grid faults. This paper introduces the performance of a DFG-based wind farm connected to a weak power system via a long transmission line and shows the quick injection of reactive current to support the grid voltage according to the grid code requirements considerably.

Regarding the performance of the wind farm in this case study the generation unit is able to raise the grid voltage at the PCC by approximately 10 % of the nominal voltage. A general conclusion for the adjustment of the reactive current controller gain connected to a weak power system is sophisticated. The voltage level, the parameter and the length of the transmission line have to take into account for each grid topology.

If the wind farm is connected to strong power system the impact of injected reactive current is insignificantly. Thus regarding the voltage level at the PCC the reactive current controller gain can be set to a small value or even to zero.

Due to the grid integration of more and more renewable energies all over the world the short circuit power of power systems will decrease. Regarding this challenge wind turbines can provide a contribution by using their fast voltage control without additional compensation devices.

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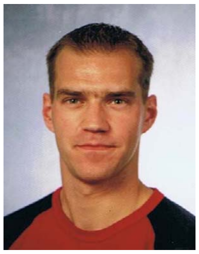
VIII. BIOGRAPHIES



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