Development of an Experimental Rig for Doubly-Fed Induction Generator based Wind Turbine

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Abstract — **This paper deals with an experimental rig for a doubly-fed induction generator (DFIG) based wind turbine developed at the University Duisburg-Essen. The authors provide an overview of the dimensioning, commissioning and operation as well as show results of the measurements and compare these with simulation results. The main focus of the paper is the practical implementation and programming of the digital signal processor (DSP). Chapter one gives an introduction, followed by a brief explanation of the DFIG concept and its control in chapter two. Chapter three deals with the equipment of the experimental rig, and this is followed by the introduction of the rapid control prototyping approach chosen for programming the DSP. The paper ends with a comparison of the results of simulations with measurements and some concluding remarks.**

Keywords – wind power, doubly-fed induction generator, rapid control prototyping, digital signal processor, fault ride through

I. INTRODUCTION

Wind energy is the most promising renewable source of electrical power generation for the future. Many countries promote the wind power technology through various national programs and market incentives. Industry associations expect an increase in the global installed wind power capacity in the medium and long term with the majority of that coming from large offshore wind parks. At the end of 2009 158 GW wind power was already installed into the electrical grids all over the world.

State of the art generators for wind turbines are equipped with power electronics to enhance the static as well as the dynamic behavior of wind turbines. Nowadays power electronics is increasingly becoming an important part of the electrical grids, for instance in modern wind turbines, HVDC transmission lines or dynamic reactive power compensation devices. Today different generator concepts for wind turbines are commonly used. 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 induction generator.

Due to increasing share of wind power, the grid integration of wind turbines has to be arranged in a way that the grid operates reliably and safely. Therefore regarding the dynamic behavior of wind turbines, certain requirements have to be formulated. According to Grid Codes all over the world, Fault Ride Through (FRT) capability is required for modern turbines. Additionally, according to certain grid codes, wind turbines have to provide voltage support during faults.

II. DOUBLY-FED INDUCTION GENERATOR

Figure 1 shows the basic concept of DFIG 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). Both converters are coupled via a DC-link capacitor. The IGBTS are controlled by pulse width modulation (PWM) signals from a DSP.

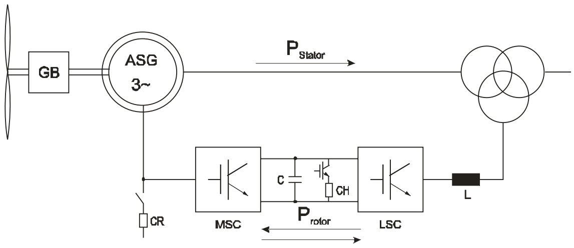

Figure 1. Basic concept of DFIG-based wind turbine

Basically the control of the DFIG can be separated into the line side converter (LSC) and the machine side converter (MSC) controls. 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 MSC controls active and reactive power of the DFIG independently from one another and follows a tracking characteristic to adjust the generator speed for optimal power generation depending on the wind speed. The theoretical background of modelling DFIG systems and its control is already published in numerous papers, e.g. [1] and [2].

The mechanical power generated by the wind turbine drives the DFIG, 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 DFIG, 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.

III. Equipment Experimental Rig

This chapter introduces the set up of an experimental rig based on DFIG technology. Figure 2 shows its three-phase circuit diagram. The rig is connected to the low voltage 400V supply.

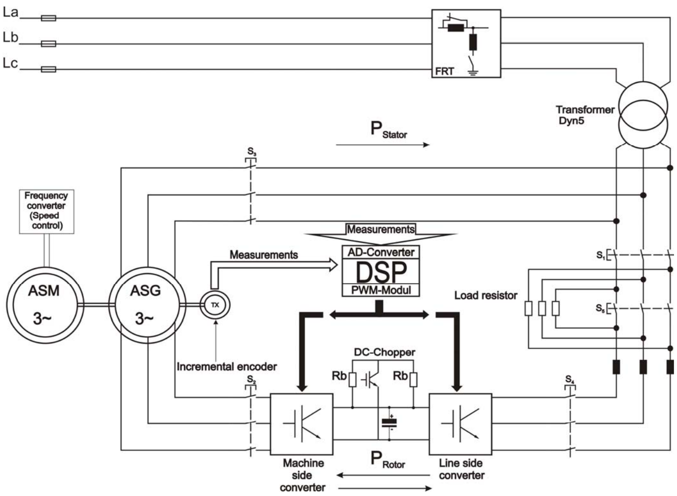

Figure 2. Circuit diagramof the experimental rig

Figure 3 shows the generator (left) and the drive of the experimental rig (right). Basically the set up contains the following six different units.

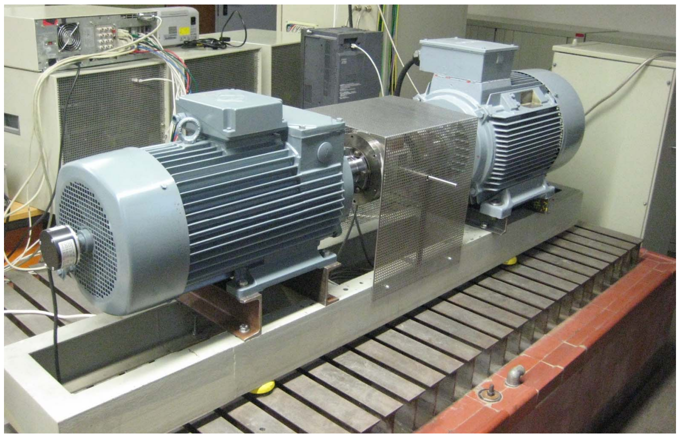

Figure 3. Drive train of the experimental rig

A. *Drive Train*

The generator is a 9 kW slip ring induction generator, which is driven by a standard squirrel cage asynchronous motor. The speed of the drive can be adjusted through a frequency converter. Using this converter the speed of the shaft can be emulated according to the speed of wind turbines and its corresponding gear box. In this arrangement a generator with two pole pairs is used.

B. *Transformer*

Typically a Dyn5 transformer connects the wind energy generation unit to the medium voltage grid, therefore the zero sequence system (e.g. during earth faults) has no effect on the transient electrical and mechanical behavior of the generator. At the experimental rig also a Dyn5 transformer is used. Its primary winding is connected to the low voltage level, while the voltage level of the secondary winding can be adjusted variably.

C. *Power Electronics*

The power electronic circuits perform the following functions; a) convert AC to DC and back to AC at variable frequency in the rotor circuit, b) control DC voltage and c) control amplitude, frequency and phase angle of rotor voltage. These functions are performed by solid state semiconductor. In state of the art wind turbines as well as in the experimental rig 2-level IGBT converters are used. The switching frequency can be adjusted variably and should be chosen in a way that the balance between switching losses and accuracy of the desired signals is achieved. In nominal operation mode 20 to 30% of the active power flows through the converter circuit and the rest through the stator.

D. *Digital Signal Processor*

The DSP is one of the core elements of the experimental rig because it contains the control and thus the technical know-how. The DSP used in this rig contains CMOS technology and has a clock frequency of 150 MHz. The 32-Bit CPU can perform fixed-point as well as floating point calculations. Inputs of the DSP are, as visualized in Figure 2, different analogue measurements of voltages and currents as well as speed and angular displacement of the generator shaft. The outputs of the DSP are the PWM signals of each IGBT. The DSP contains a 16 channel AD converter with a 12 bits resolution.

E. *Inductive Voltage Divider*

The experimental rig has FRT testing capability. Therefore an inductive voltage divider is used to produce voltage dips with defined depths and durations according to certain grid code requirements. The inductive voltage divider includes a serial and a parallel three phase inductance. For each phase thyristor based semiconductor contactors are used to enable switching of balanced as well as unbalanced short circuits to the generator system. Figure 3 describes basic setup for FRT testing.

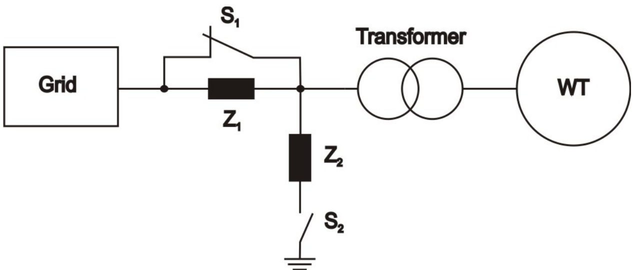

Figure 4. Basic set-up for FRT testing

IV. Rapid Control Prototyping Approach

Efficiency and flexibility are of great importance in research and development processes all across industrial fields. This also applies to the development, the implementation and the commissioning of control algorithms for electrical drive engineering. The rapid development in computer technology during the past decades has revolutionized the field of control techniques for electrical machines and enabled much more complex and efficient control algorithms, which nowadays usually are implemented on microprocessors.

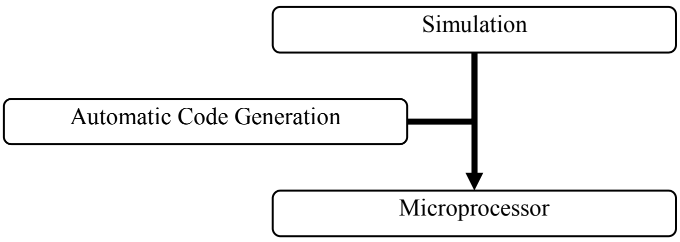

Figure 5. Process of programming in the simulation environment

The process of programming a microprocessor for real time applications is a tedious and time consuming task usually done in assembly language or C. However a new approach for microprocessor programming has been developed in the recent years. It is referred to as Rapid Control Prototyping (RCP) and has made the programming process more graphical and thus intuitive. Figure 5 shows the basic concept. The graphical user interface is block-oriented and out of this scheme the DSP code is auto generated by the RCP environment. In general this approach is much faster than writing the code manually. Thus the developer can spend more time on improving the functionality and performance of the program. This automatic code generation function is included in certain simulation environments.

Simulating the real-time behavior of the hardware and its control without the need of hardware implies a fast method to enhance the control of an already existing physical system. Thus a fast improvement and adjustment can be achieved due to automatic code generation. Also important is that different subsystems can be developed and tested in parallel in order to shorten the development process.

The graphical programming environment leads to a simplified and clear language for the group of persons who are involved in the development process. Block-oriented programming also results in an easy way to document control concepts and complete processes. Due to the high level of automation the amount of returning tasks or functions can be minimized.

Another aspect is that debugging is sophisticated regarding real-time applications. By using RCP the analysis of control algorithms and its faults can be done at first in the simulation environment. After the simulation shows the expected or unexpected results, the improvements can be implemented to the real–time application at the microprocessor. That makes the process of enhancing the performance of the control algorithm more efficient and faster. For instance changing parameters of the certain controller requires experience and an intuitive feeling. By using RCP experience is still required, but the RCP approach is well suited for the first steps towards improvements of the controller.

Finally, the following points summarize the central advantages of the RCP approach:

- Fast and cost-efficient commissioning of different control methods
- Shortening of the development process
- Simplified and intuitive programming
- Comparison between simulation and application
- Simplified debugging
- Parallel development of certain subsystems

Disadvantages of the RCP method are the additional costs due to additional software tools and the memory consuming programming style. The second aspect leads to the fact that for a memory and execution time optimized application the RCP approach is not suitable.

A. *Automatic Code Generation*

Automatic code generation is the core element of an RCP approach. Figure 6 presents the process from the model and its simulation to the implementation at the microprocessor and its necessary transformations. The steps shown from the graphical programming environment across the high-level language and the assembler code to the resulting binary code will be performed by the simulation environment automatically.

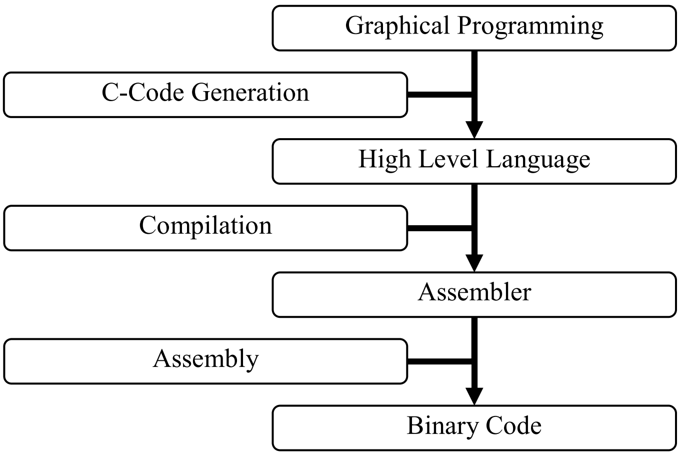

Figure 6. Scheme of automaical code generation process

The automatic code generation function is implemented by the numerical simulation environment Matlab/Simulink. Specific toolboxes of Matlab/Simulink allow direct communication between the graphical user interface of Simulink and the DSP. These toolboxes only support certain DSPs. Toolboxes for these DSPs include optimized blocks for the utilization in power drive engineering, like for instance a space vector generator block or Park, Clarke and its inverse transformation block.

B. Simulation

For a realistic behavior the sample time of the simulation has to be separated into two step sizes. One sample time correlates with the sample time of the DSP. At the experimental rig the switching frequency of the IGBTs is 5 kHz. That means that the sample time of control block in the simulation is determined as 200 µS. Besides the control of the DFIG the simulation of the hardware components should carry out results with a higher accuracy. Therefore the step size of the hardware unit is 1µS. Figure 7 shows the main elements of the simulation.

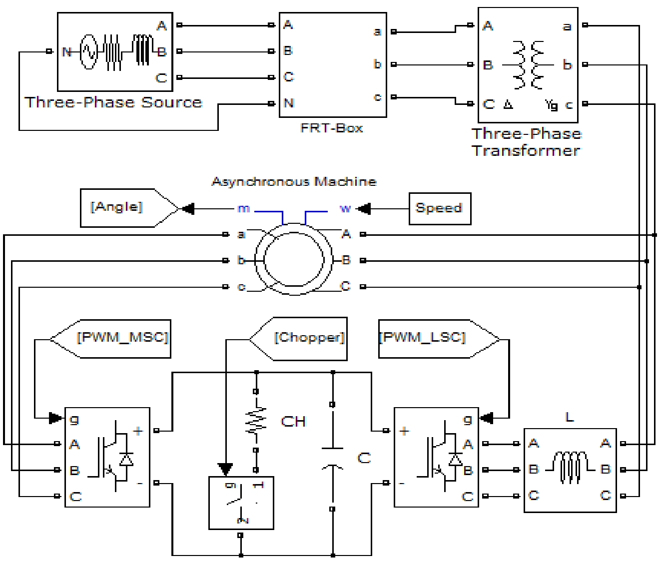

Figure 7. Matlab Simulation DFIG

Figure 8 shows the different inputs and outputs of the control of DFIG simulation. As inputs different measurements of voltage and current as well as the angular displacement of the rotor shaft are required. For passing on set-points to the system a third input is needed. The outputs of the simulation are the PWM signals and the control of the chopper IGBT in the DC circuit.

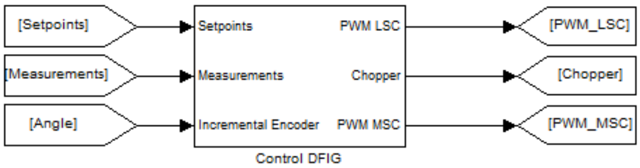

Figure 8. Inputs and Outputs of DFIG control

C. Implementation

Figure 9 and 10 give an idea of how the graphical programming environment is structured. It is completely different from the user interface of C programming tools. Figure 9 shows the main interrupt of the voltage oriented control of the DFIG. Different setpoints are transmitted asynchronously to the main loop. The icon of the selected DSP allows a simplified communication with the microprocessor.

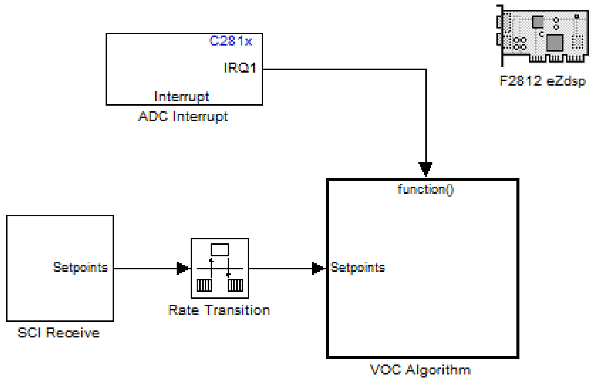

Figure 9. Main interrupt of voltage oriented DFIG control

Figure 10 displays the main control algorithm behind the voltage oriented control block of figure 9. The same input and output structure is used as already seen in Figure 8. That implies that the equivalent control algorithm is used in the simulation as well as at the microprocessor.

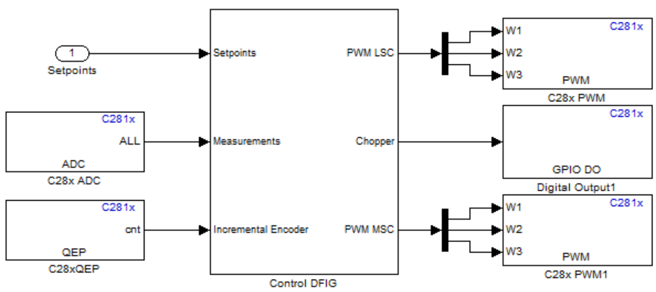

Figure 10. Inputs and Outputs DSP control of the DFIG

V. Simulation and Measurements

For purposes of demonstration, the behavior of the DFIG during a balanced fault is shown. Fig. 11 shows simulation results, while the measurement results on the experimental rig for an identical fault are shown in Fig. 12 The generator operates with the nominal power of 9 kW while the power factor is one. A balanced voltage dip is created using the inductive voltage divider. The remaining voltage is 66.6 % during the three phase short circuit of 150 ms. The diagrams show (from top to bottom) the instantaneous values of the phase-to-phase voltages at the secondary terminal of the transformer, the total active and reactive power of the

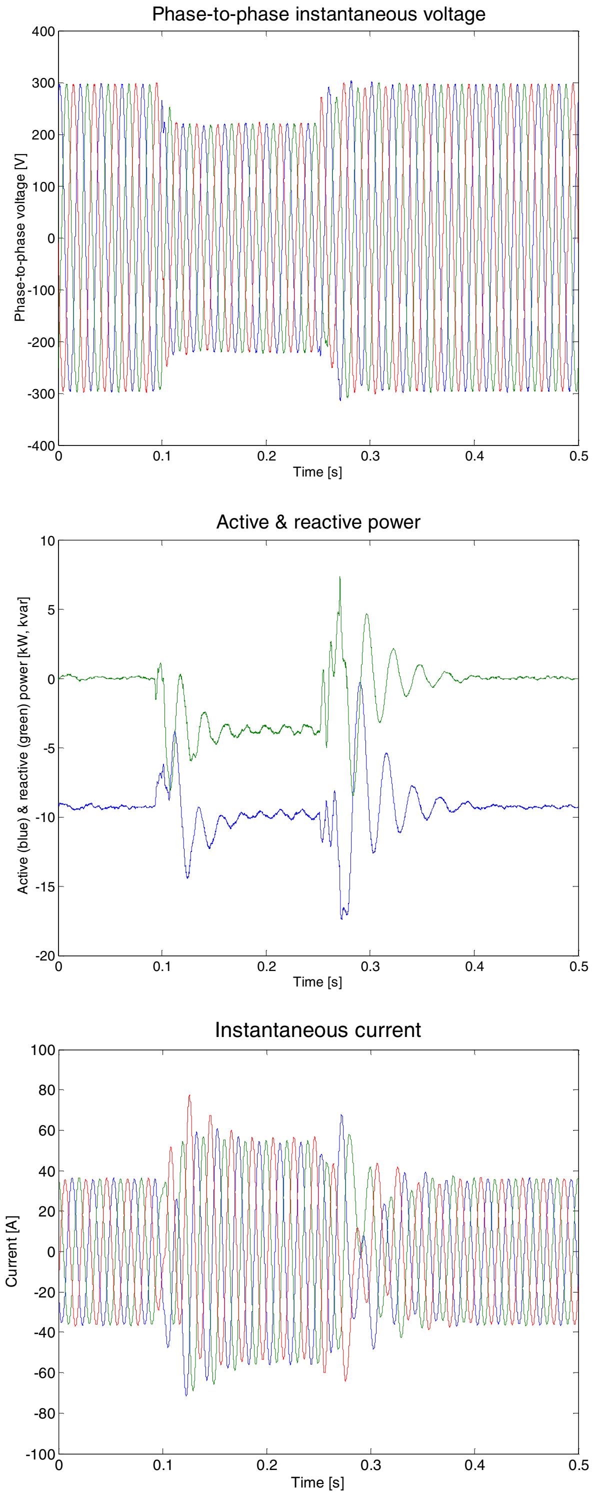

Figure 11. Simulation results of the DFIG experimental rig

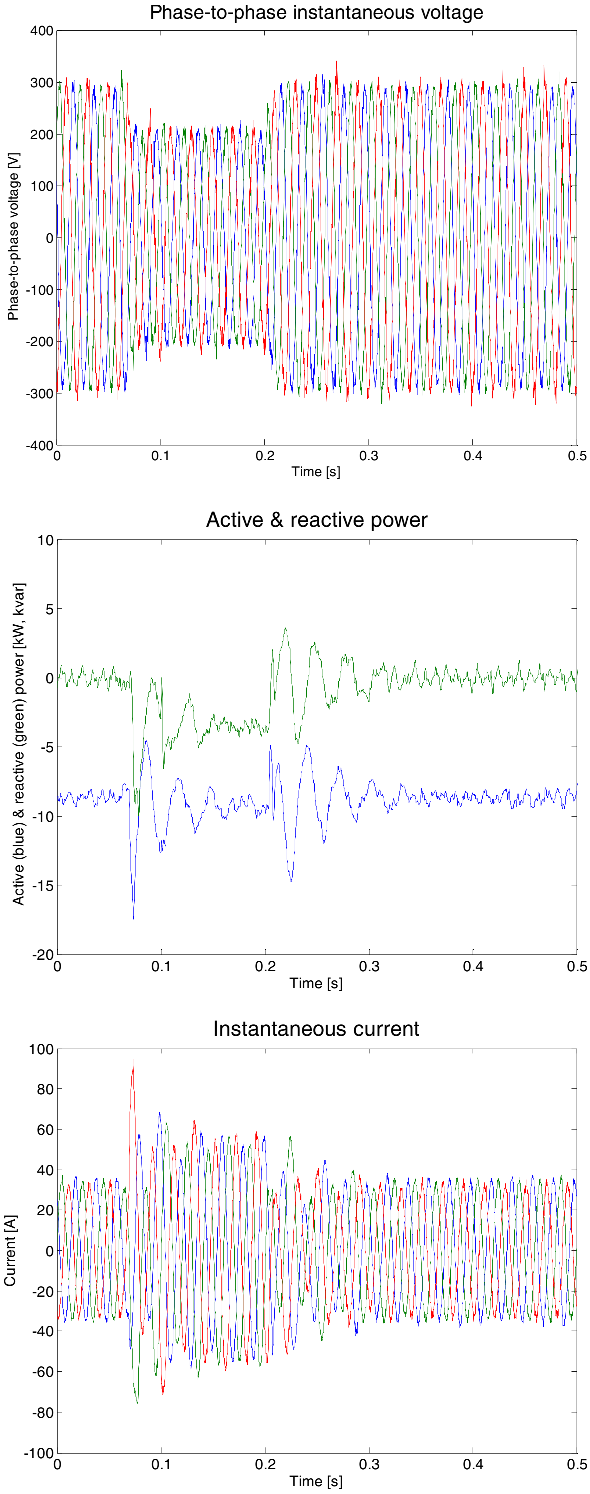

Figure 12. Measurmentsof the DFIG experimental rig

DFIG system and finally the instantaneous values of the total currents at the secondary terminal of the transformer. Since the consumer oriented sign convention has been used, the generated active power as well as the capacitive reactive power turn out to be negative.

Basically the DFIG of the experimental rig shows the FRT capability. The generator remains connected to the grid during the three phase short circuit. The current peak values are high but in an acceptable range. According to voltage support principles of the German transmission system operators, the DFIG provides capacitive reactive current during the fault. The comparison between simulation and measurement makes clear that the diagrams show a sufficient correlation. The ripples in the active and reactive power measurements occur due to the measuring inaccuracy of the corresponding voltages and currents. The product of both current and voltage errors result in visible active and reactive power ripples. The focus of the presented results is not to optimize the accuracy of certain measurements, the main focus rather is to visualize and demonstrate the dynamic behavior of DFIG systems in principle. The fast control algorithm of the IGBT converters leads to the fast step response of the active and especially the reactive power during grid disturbances.

VI. Conclusion

The paper overviews the development and the operation of an experimental rig for DFIG based wind turbine. The DFIG system and its control are explained briefly. Furthermore the main components of the experimental rig and their functions are introduced.

As an essential element the chosen rapid control prototyping approach is presented. The implementation makes use of the basic advantages of this programming method. The main advantage is the possibility to program a microprocessor from the simulation environment. That implies that the engineer can achieve a functional code in a very short time frame. This is supported by the simple and intuitive programming environment and its graphical user interface. Shortening the whole development process of control applications is another important benefit of the RCP approach. The advantages mentioned above outweigh the disadvantages. Disadvantages are the additional costs and the memory consuming programming style. The comparison between simulation and measurement emphasizes that the RCP approach is well suited for the utilization in electrical drive engineering. For an execution time optimized application the RCP approach is probably not the best choice.

Regarding grid integration the DFIG system of the experimental rig can fulfill the electrical requirements of modern grid codes. The generator system demonstrates the required FRT capability. The simulation and the measurements show that the generator remains connected to the grid during grid faults. According to the requirements of global grid codes the DFIG provides capacitive reactive power to support voltage stability.

The implementation of already existing control algorithms dealing with the dynamic behavior of the DFIG during unbalanced faults will be the focus of the future research.

VII. References

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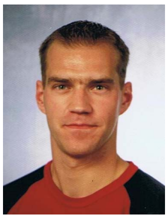
VIII. Biographes



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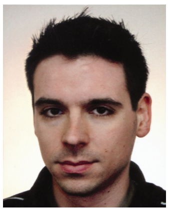

Christian Feltes (1979) received his Dipl.-Ing. degree in electrical engineering from University of Duisburg-Essen/Germany in 2005. Since January 2006 he is doing his Ph.D. studies in the Department of Electrical Power Systems at the same University. His research interests are focused on wind energy generation, control, integration and dynamic interaction with electrical grid. He is student member of IEEE.

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.