Comparison of the Grid Support Capability of DFIG-based Wind Farms and Conventional Power Plants with Synchronous Generators

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Abstract-- **Current grid codes stipulate the same or similar behaviour during grid faults for wind turbines as for conventional power plants based on synchronous generators. But the technology and control of both devices is completely different. Since modern wind turbines use IGBT-based frequency converters, they provide a very fast control with the disadvantage of tight thermal limits for the IGBTs. The excitation control of synchronous generators is rather slow and has nearly no effect on the transient process during faults. Only the synchronous generator itself provides good grid support during severe faults by virtue of its large overload capability. This paper compares both generation techniques through conceptual discussion and based on simulation results. The results show that there are significant differences in terms of their behaviour during grid faults. The results also point to the need for a revision of the current grid codes with respect to more dedicated requirements.**

***Index Terms*—Wind power, control system, doubly-fed induction generator, grid codes, fault ride-through, voltage support.**

I. INTRODUCTION

With the strong increase in renewable energy generation during the last years, especially in the wind energy sector, new grid codes have been released, stipulating particular requirements concerning grid support during steady-state operation and grid faults. Most grid codes prescribe a similar behavior both for the conventional power plants with synchronous generators (SG) and wind based power generation plants [1,2]. However, most of the renewable generation systems are based on other generation principles and use modern control hardware such as frequency converters with power electronic devices. For example, in modern wind turbines, the doubly-fed induction generator (DFIG) is the most commonly used generator type, followed by the full-sized converter generator (FCG). The performance of these devices is primarily determined by the features and technical limits of their power electronic devices. Typical behaviors include a very fast system response, which offers various control options, but also tight thermal limits, which necessitates fast and reliable protection devices. By contrast, the control of a conventional power plant with SG is rather slow, but provides a huge overloading capability for a relatively wide time window. The dynamic behavior during and immediately after fault clearing is dominated by the inertial response of the SG, which then is followed by transients affected by the excitation system. These significant differences should be considered in an appropriate way in modern grid codes and will therefore be discussed in this paper in detail. To highlight the differences, the behavior of a conventional power plant equipped with SG and a wind farm consisting of DFIG-based wind turbines with the same total capacity, will be compared based on simulation results.

Section II shows the hardware and control setup of a conventional power plant with SG. In section III, a typical modern wind farm consisting of DFIG-based wind turbines is introduced and control options and limitations discussed. Section IV shows simulation results for comparison of both generation technologies and section V finally draws some conclusions.

II. CONVENTIONAL POWER PLANT WITH SYNCHRONOUS GENERATOR

For purposes of comparison, a small conventional power plant using a cylindrical rotor SG with a nominal power of 62.5 MVA (50 MW) has been selected. The configuration is shown in Fig. 1. The excitation system is based on an alternator-rectifier brushless exciter with rotating diodes [3,4].

The focus of this paper is set on the behavior during grid faults of about 150 ms duration. This time span is too short for the excitation control to considerably affect the response of the generator. For the same reason, the governor system was not simulated in this study, and the generator is assumed to operate with constant prime mover power. The dynamical behavior of the SG is well-known and has been dealt with in

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several books and papers. Hence, a detailed description is skipped here in favor of a more detailed discussion of the dynamic behavior and control of the DFIG system.

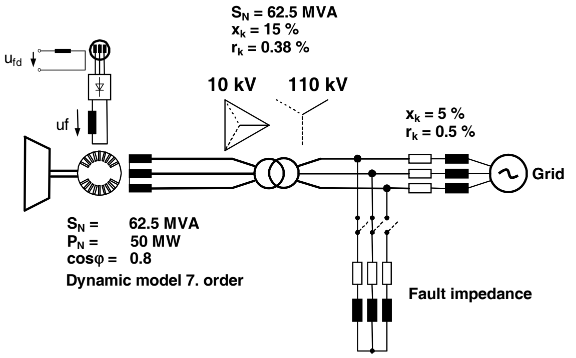

Fig. 1. System configuration of the synchronous generator with brushless excitation system and reference data of generator, grid and simulated fault

III. DFIG BASED WIND FARM

The wind farm to be studied also has a total capacity of 50 MW and is connected to the same test grid as the conventional SG to allow a direct comparison of the two generation concepts. For all tests, the wind farm is assumed to operate at nominal power and unity power factor. Fig. 2 shows the layout of the wind farm.

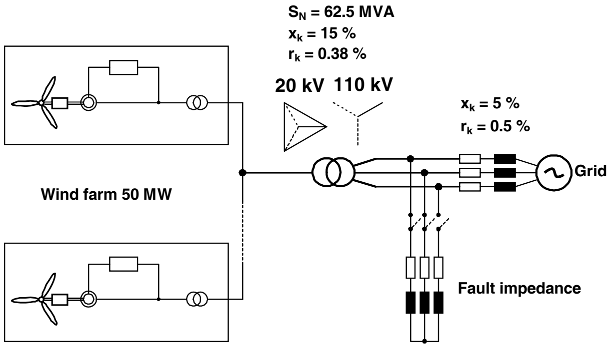

Fig. 2. System configuration of the wind farm consisting of DFIG-based wind turbines and reference data of transformer, fault and grid

Fig.3 shows the system configuration of the DFIG-based wind turbines. The main components of the WT are:

- Rotor blades
- Gearbox (GB)
- Slip-ring induction generator (SRIG)
- Machine-side converter (MSC)
- Line-side converter (LSC)
- Machine transformer (Tr)
- Filter (Filt) for reduction of switching harmonics
- Rotor-crowbar (CR) and chopper (CH) for converter protection

The main parts of the DFIG system are the Slip Ring Induction Generator (SRIG) with three-phase stator and rotor windings and the back-to-back PWM converter. The converter uses self-commutated IGBT switches and allows operation in all four quadrants. It is connected between the rotor circuit of the generator and the grid. The MSC operates at slip frequency and controls active and reactive power at the generator stator terminals. The LSC maintains the DC voltage and feeds the rotor power into the grid [5]. The direction of the power flow through the converter depends on the operating point of the generator. In sub-synchronous operation, the power flow is directed from the grid into the rotor circuit, while the power flow direction reverses in super-synchronous mode. Since the converter allows decoupled control of active and reactive power, the LSC can also be used for voltage support through reactive current in-feed in steady-state and during grid faults [6]. The distribution of reactive power flow between stator and LSC can be optimized for minimization of loss and/or thermal loads. Normally, during steady-state operation the LSC only provides a small reactive current contribution. However, during grid faults the current capacity of the LSC is fully used to support the grid, because the response of LSC is faster than that of MSC.

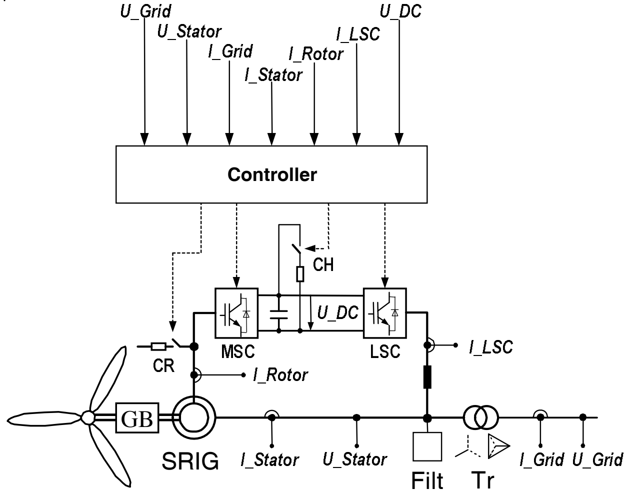

Fig. 3 DFIG-based wind turbine, main system components and measured quantities for converter control

To guarantee the secure Fault Ride-Through (FRT) capability of the DFIG, the protection devices crowbar and chopper are indispensable [7]. When a grid fault occurs, the voltage drop at the terminal can lead to high DC currents in the generator stator winding. This current component appears as AC current with high peak values on the rotor side, resulting in an abrupt charging of the DC circuit. The ensuing overvoltage would, without protection devices, lead to the destruction of the DC capacitors due to overvoltage. The task of the DC chopper and the AC crowbar is to limit the DC voltage to an acceptable level, by different means. The DC chopper uses an IGBT switch to short-circuit the DC circuit through a braking resistor and thus to dissipate the waste energy that cannot be fed to the grid by the LSC. This method allows a continuous control of the generator currents, but requires additional IGBT switches and braking resistors. The AC crowbar uses thyristor valves to short circuit the rotor through the crowbar resistors, which constitute three resistors in star or delta connection. On the one hand, this method is cheaper and provides a reliable protection for the converter, since it is decoupled from the rotor circuit during crowbar ignition. On the other hand, for the duration of crowbar ignition (approx. 100…120 ms) the generator control is lost and the generator acts as a normal induction generator, which consumes reactive power. From grid point of view, this is not acceptable. In modern DFIG systems a compromise between the size of the crowbar and the chopper is struck. For example, it is possible to design the chopper in such a way that the crowbar is not activated except during internal faults.

A. DFIG control options and limitations

Since the DFIG control is based on a fast IGBT converter, it offers several control options during steady state operation and grid faults. In steady state, it primarily controls the generator speed in accordance with a specified tracking characteristic to optimize the power output from the wind turbine. The reactive power channel can be used to control the grid voltage or follow instructions of the dispatcher like power factor or reactive power setpoints [8]. During grid faults the reactive power control of both MSC and LSC can be used to support the grid through reactive current in-feed. The control structure of the DFIG-based wind turbines to be used in this study is based on a feedforward decoupled current control for MSC and LSC. The structure is shown in details in previous papers [6,9].

The effectiveness of the voltage support through DFIG-based wind turbines is mainly determined by the converter current limits and the pre-fault operating point. The LSC current magnitude is limited by its control with priority for active current, because it has to be ensured that the DC voltage is maintained. Accordingly, the reactive current is limited to:

$$i_{LSCr,max} = \sqrt{i^2_{LSC,max} - i^2_{LSCa}} \tag{1}$$

$i_{LSCr,max}$: Maximum reactive current at LSC

$i_{LSC,max}$: Maximum current magnitude at LSC

i_{LSCa}: Active current at LSC

The behavior of the active current strongly depends on the DC voltage controller response. The steady-state value (after transient oscillations have died down) is:

$$i_{LSCa} = \frac{p_{LSC}}{u_{LSC}} = \left(\frac{s \cdot p_s}{s-1} - p_{loss}\right)\frac{1}{u_{LSC}} \tag{2}$$

p_{LSC}: LSC active power

u_{LSC}: LSC voltage

p_s: Stator active power

s: Machine slip

p_{loss}: Converter losses

The converter current limit can be fixed or variable. In the latter case a thermal model of the converter can be used to calculate the dynamic current limits to allow temporary overloading without the risk of damaging the converter.

The reactive current capability of the generator stator is determined first and foremost by the MSC current limit. In a reference frame aligned to the stator voltage (denoted by $\angle us$), the stator reactive current is controlled through the q-axis rotor current, which is limited by the control to:

$$i^{\angle us}_{MSCq,max} = \sqrt{i^2_{MSC,max} - i^{2\angle us}_{MSCd}} \tag{3}$$

$i^{\angle us}_{MSCq,max}$: Maximum MSC q-axis current

$i_{MSC,max}$: Maximum MSC current magnitude

$i^{\angle us}_{MSCd}$: MSC d-axis current

Again, the converter current limit can be fixed or variable for the same reason as for the LSC.

It follows from the equations of the induction generator [9], after neglecting the small stator resistance, for the maximum q-axis stator current in overexcited mode of operation:

$$i^{\angle us}_{Sq,max} = \frac{l_m}{l_s} i^{\angle us}_{MSCq,max} - \frac{u_S}{\omega l_s} \tag{4}$$

$i^{\angle us}_{Sq,max}$: Maximum q-axis stator current in overexcited mode

ω: Grid angular frequency

l_s, l_m: Stator and mutual inductance of the DFIG

In a stator voltage oriented reference frame, the maximum stator reactive current $i_{Sr,max}$ in overexcited mode is:

$$i_{Sr,\max} = -i^{\angle us}_{Sq,max} \tag{5}$$

The total reactive current $i_{r,max}$ available for grid voltage support during voltage dips from a DFIG is:

$$i_{r,max} = i_{Sr,max} + i_{LSCr,max} \tag{6}$$

Fig. 4 shows the maximum reactive current at stator terminals, LSC and the total in overexcited mode as a function of the grid voltage. The diagram shows the current limits for a DFIG with a fixed current magnitude limit of 1.3 p.u. at MSC and 0.4 p.u. at LSC for operation at nominal active current and for zero active current.

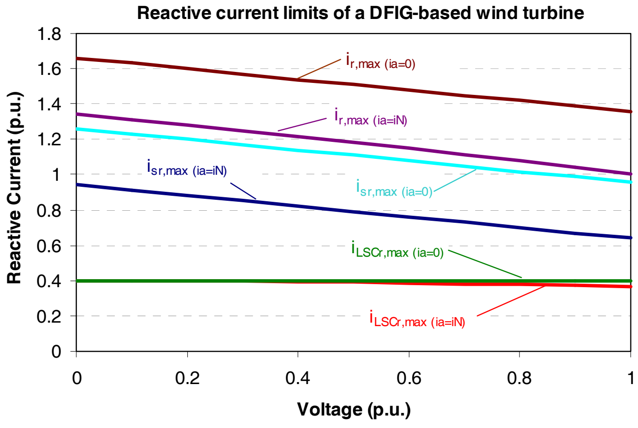

Fig. 4 Reactive current limits of a DFIG at nominal and zero active current

It is obvious that a reduction of active current during severe grid faults is recommendable to increase the voltage support capability of the DFIG.

The current limits discussed so far are only valid for symmetrical operation. For unbalanced faults the negative sequence currents have to be considered. Most DFIG-based wind turbines have a negative sequence current control at least at the LSC. It reduces the negative sequence currents during unbalanced faults to a small value, ideally to zero. For the LSC this negative sequence control is easy to implement, because LSC voltage adjustment range is sufficient for most unbalanced fault scenarios [10]. Additionally, the WT transformer is connected in Dyn, so that there is no overvoltage at the LSC in case of an earth fault in the medium voltage network. In other words, with a proper negative sequence control, the reactive current limit for the positive sequence at LSC is not affected.

However, a negative sequence control at the MSC is less effective, because the adjustment range of the MSC voltage is not sufficient to compensate the negative sequence currents for severe faults [11,12]. That means during severe unbalanced faults there are residual negative sequence currents at the MSC, whose magnitude depends on the negative sequence voltage at the stator and on the performance of the implemented negative sequence control. These currents entail an additional thermal load to the MSC. To avoid overloading of the MSC, the negative sequence current has to be considered in the current limitation for the positive sequence. As a result, the voltage support capability of the DFIG through reactive current in the positive sequence is reduced during unbalanced grid faults. However, the negative sequence current, which flows through the DFIG stator, lowers the negative sequence voltage within the grid, which might be more favorable to the grid.

IV. SIMULATION

The simulations presented here have been carried out with MATLAB/Simulink with SimPowerSystems Toolbox in the time domain based on instantaneous values. For the comparison of both generation concepts the system configurations described in sections III and IV have been studied and different faults were simulated. Prior to fault both generation units were operating at nominal active power at a power factor of unity.

Fig. 7 shows the simulation results for a three-phase fault in the HV grid which reduces the voltage to 15% of the nominal voltage at the HV side of the plant transformer. The short circuit currents of the SG contain large DC components, which decay with a large time constant. The DC components in the short circuit currents of the DFIG decay much faster. The active current at the SG is determined by the rotor angle and cannot be controlled during fault. On the other hand, the DFIG reduces its active current during fault and ramps it up after voltage recovery. The active power ramp up reduces mechanical stress due to drive-train oscillations and is also specified in current grid codes. The ramp steepness can be set in the DFIG control. During the voltage dip the SG feeds in a higher reactive current compared to the DFIG system. The DFIG is controlled with a reactive current limit of 1 p.u., which is the minimum requirement in [1]. Of course, the reactive current limit of the DFIG can be increased at cost of a further reduction of the active current, as shown in section IV. After fault clearing the DFIG reduces the reactive current to zero immediately, whereas the SG goes to underexcited mode for at least one second. This fact in combination with the increased active current in-feed countervails the voltage return.

Fig. 8 shows the results for a symmetrical fault with a voltage dip to approx. 80% of the nominal voltage at the HV side of the generator transformer. In this scenario the DFIG-based wind farm is operated with a continuous voltage control at high gain ($\Delta I_r/\Delta U = 6.6$ p.u.). In [1] a minimum gain of 2 p.u. is required, so that the maximum value of 1 p.u. is reached at a voltage drop to 50%. A higher gain results in an optimized voltage support, even for smaller voltage dips. This allows the full reactive current to be fed in to the grid even for distant faults. In the simulation results in Fig. 8 the DFIG feeds in approx. the double reactive current of the SG. The active current curves in this case are very similar, since the active power of the DFIG is not reduced during this fault.

Fig. 9 and Fig. 10 show the simulation results for a two-phase fault at the HV terminals of the plant transformer. The SG (Fig. 9) deals with the natural response and feeds in positive and negative sequence currents without a limitation. Since a fast current limitation is not possible with the slow excitation control, the system has to be designed for these currents anyway. However, for the DFIG the response strongly depends on the implemented control. Fig. 10 shows the results for a DFIG system with and without negative sequence control at the MSC. In case of the system without negative sequence control at the MSC (labeled as DFIG2), the negative sequence currents are large and the converter is operated at its current limit. Thus, the positive sequence currents are reduced with priority to the reactive current. In case of a DFIG system with negative sequence control at the MSC (labeled as DFIG), the negative sequence currents are reduced. Depending on the needs of the system operator, an optimized tradeoff between positive and negative sequence voltage support can be implemented in the DFIG control system.

V. CONCLUSION

In this paper a comparison between a conventional power plant and a DFIG-based WF has been done based on the technical options and limits concerning grid voltage support during faults. During deep voltage sags, the SG feeds in more reactive current than the DFIG-based WF and thus gives a stronger support to the grid voltage. However, for smaller voltage dips resulting from distant faults, the DFIG can feed-in higher reactive currents. While in the SG the transient reactive current is determined by the generator parameters, the fast control of the DFIG allows the adjustment of the reactive currents within the current limits of the system during faults. The largest difference between the two systems can be seen during unbalanced faults, where the DFIG has to reduce the positive sequence currents to avoid thermal overloading of the converter.

Due to the differences in the behavior of the studied systems, modern grid codes could formulate requirements that are more dedicated to the generation concepts. This could be done by stipulating higher gains for the voltage support characteristics in converter based generators during both grid faults and voltage recovery after grid faults, and by consideration of the real technical limits of the systems.

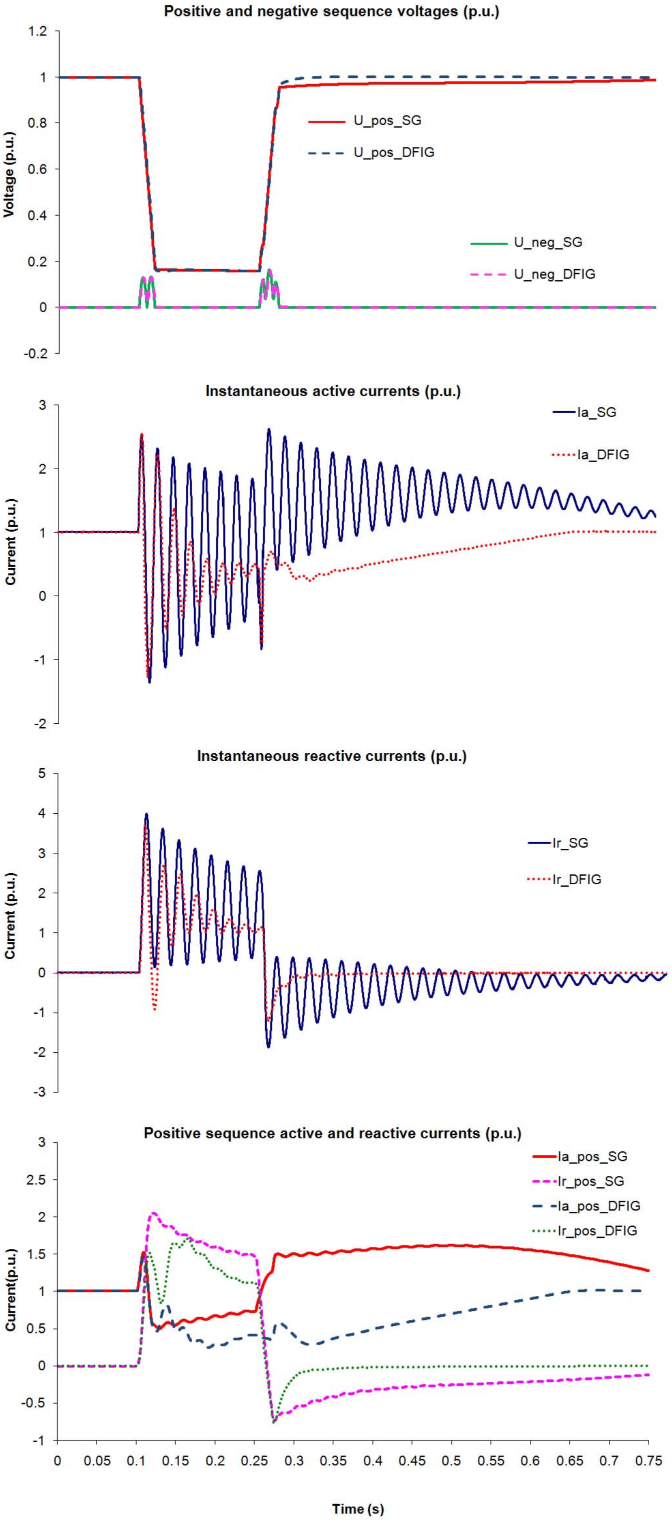

Fig. 5 Simulation results for a three-phase symmetrical fault with a resulting voltage drop to 15% of the nominal voltage on the 110kV side of the block transformer. The same fault scenario has been simulated with a conventional power plant with synchronous generator and a WF with DFIG-based WTs. Voltages shown on HV side, currents on MV side.

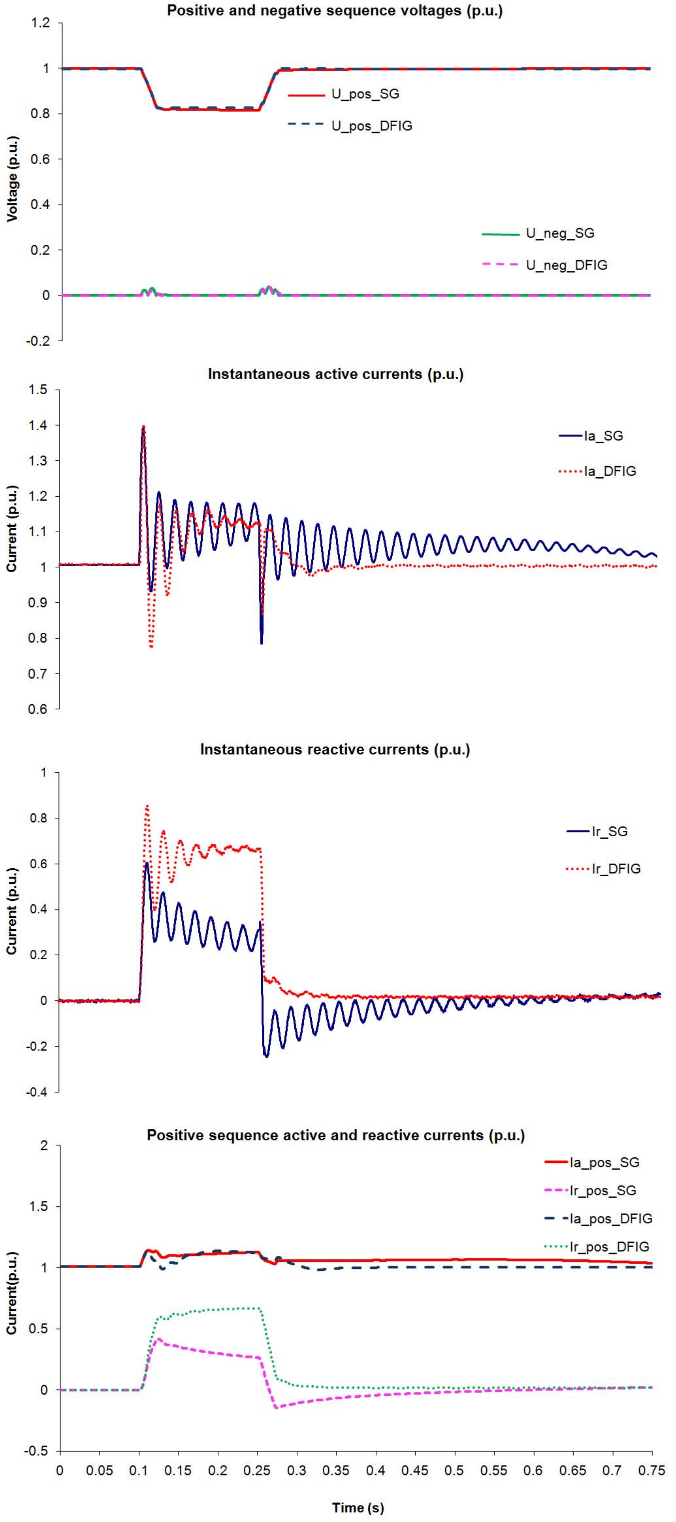

Fig. 6 Simulation results for a three-phase symmetrical fault with a resulting voltage drop to 80% of the nominal voltage on the 110kV side of the block transformer. The same fault scenario has been simulated with a conventional power plant with synchronous generator and a WF with DFIG-based WTs. Voltages shown on HV side, currents on MV side.

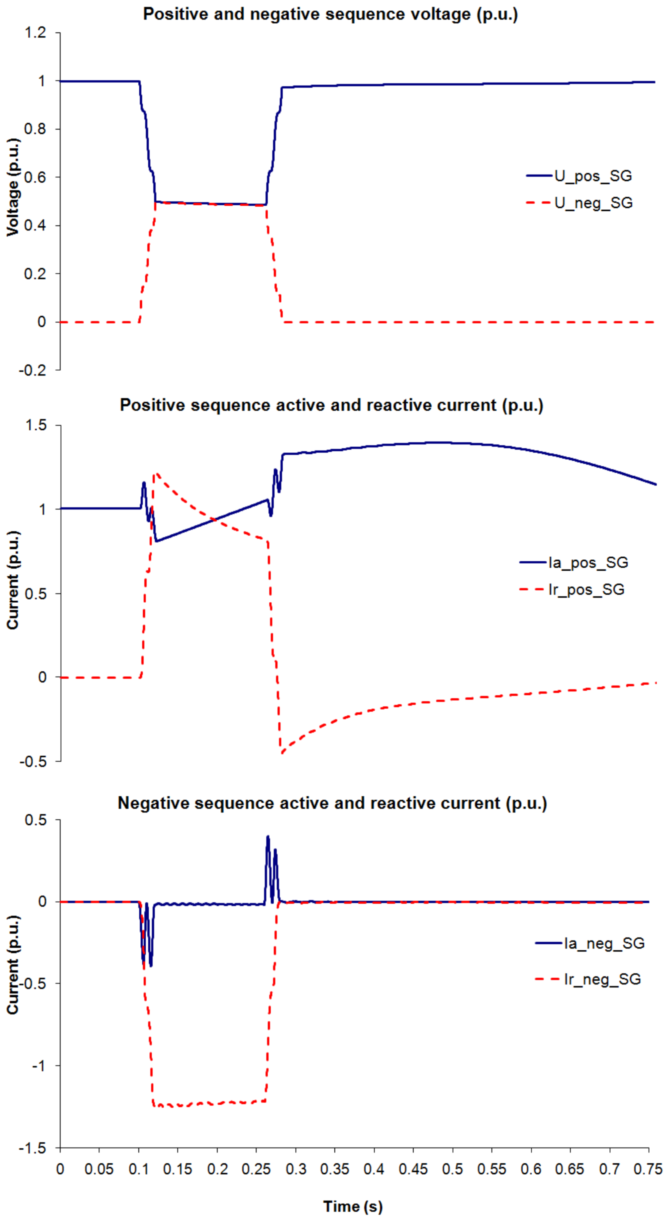

Fig. 7 Simulation results for a two-phase fault on the 110kV bus bar of the block transformer of a conventional power plant with synchronous generator. Voltages are shown on HV side, currents on MV side.

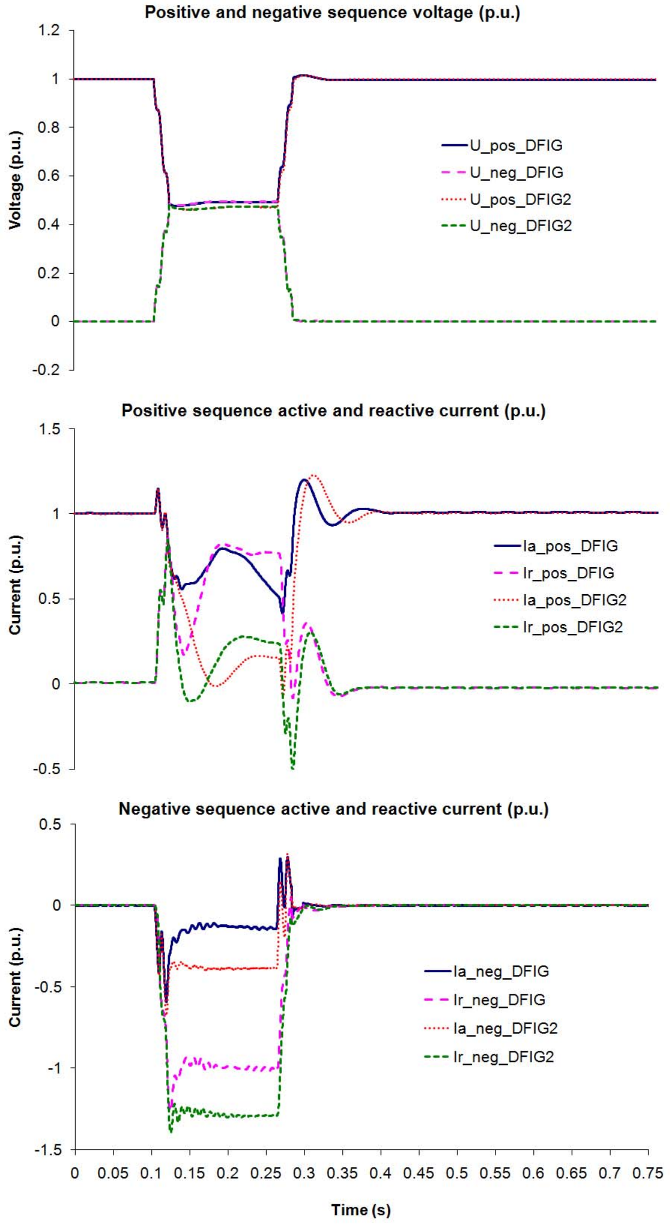

Fig. 8 Simulation results for a two-phase fault on the 110kV bus bar of the block transformer of a DFIG-based wind farm with and without negative sequence control. Voltages are shown on HV side, currents on MV side.

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VII. BIOGRAPHIES

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.

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Jörg Kretschmann (1958) received his Dipl.-Ing. degree in electrical engineering from the Technical University Berlin, Germany, in 1986. In the period of 1986 to 1988 he worked for engineering department of AEG-Kanis in Essen, manufacturing of synchronous generators up to 200 MVA. Since 1988 he is with Woodward SEG GmbH & Co. KG, Kempen/Germany, as a designing engineer for speed-variable applications: uninterruptible power supply, shaft alternators, DFIG for wind turbines. His main field is simulation of power converter systems, design of power components, passive grid-filter.

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Friedrich W. Koch (1969) received his Dipl.-Ing. degree in electrical engineering from the University of Siegen, Germany in 1998. From 1998 to 2000 and 2005 to 2006 he worked as engineer, project manager and finally as head of group in the field of industrial and power plants for the SAG GmbH. In between from 2000 to 2005 he worked on his PhD in the Department of Electrical Power Systems at the University of Duisburg - Essen, Germany. Since 2006 he is with REpower Systems AG, Germany as head of the group "Grid Integration / Simulation".

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.