Ridethrough of Wind Turbines with Doubly-Fed Induction Generator During a Voltage Dip

Johan Morren, *Student Member, IEEE,* and Sjoerd W. H. de Haan, *Member, IEEE*

***Abstract*—In this paper, a solution is described that makes it possible for wind turbines using doubly-fed induction generators to stay connected to the grid during grid faults. The key of the solution is to limit the high current in the rotor in order to protect the converter and to provide a bypass for this current via a set of resistors that are connected to the rotor windings. With these resistors, it is possible to ride through grid faults without disconnecting the turbine from the grid. Because the generator and converter stay connected, the synchronism of operation remains established during and after the fault and normal operation can be continued immediately after the fault has been cleared. An additional feature is that reactive power can be supplied to the grid during long dips in order to facilitate voltage restoration. A control strategy has been developed that takes care of the transition back to normal operation. Without special control action, large transients would occur.**

***Index Terms*—Doubly-fed induction generator (DFIG), protection, wind power generation.**

I. Introduction

THE worldwide concern about the environment has led to increasing interest in technologies for generation of renewable electrical energy. One way of generating electricity from renewable sources is to use wind turbines. The most common type of wind turbine is the fixed-speed wind turbine with the induction generator directly connected to the grid. This system has a number of drawbacks, however. The reactive power and, therefore, the grid voltage level cannot be controlled; the blade rotation causes power variations and, therefore, causes voltage variations from 1 to 2 Hz in the grid. The induction generator dynamics have resonance peaks of approximately 10 Hz. The sensitivity to flicker is high at this frequency [1].

Most of the drawbacks that are mentioned are avoided when variable-speed wind turbines are used. These turbines improve the dynamic behavior of the turbine and reduce the noise at low wind speeds. The power production of variable-speed turbines is higher than for fixed-speed turbines, as they can rotate at the optimal rotational speed for each wind speed. Other advantages of variable-speed wind turbines are that they reduce mechanical stresses, they improve power quality, and that they compensate for torque and power pulsations [2].

The disadvantage of the variable-speed turbine is a more complex electrical system, as a power-electronic converter is needed to make variable-speed operation possible. Due to the converter that is needed, the price of variable-speed turbines tends to be higher than constant speed turbines. A straightforward way to obtain variable speed is to connect a converter directly between the stator circuit of the generator and the grid. This converter has to be designed for the rated power of the turbine. An alternative concept, shown in Fig. 1, is a wind turbine with a doubly-fed induction generator (DFIG), where the converter is connected to the rotor windings. Compared to the turbines with the converter connected to the stator, the DFIG has a number of advantages. The converter is much cheaper, as the inverter rating is typically 25% of total system power, while the speed range of the generator is ±33% around the synchronous speed. Also, the inverter filters are much cheaper as they are also rated at 25% of the total power. Further, power-factor control can be implemented at lower cost, because the DFIG basically operates similar to a synchronous generator [2].

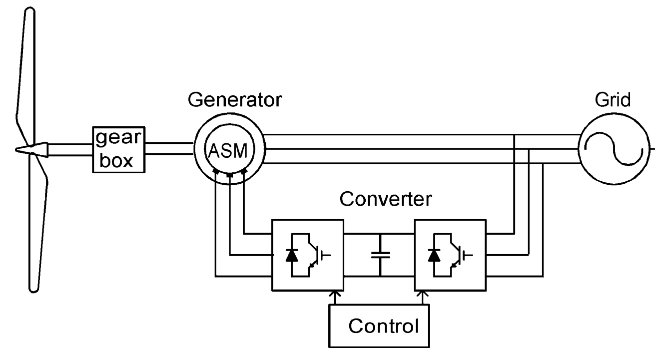

Fig. 1. Wind turbine with DFIG.

A major drawback of variable-speed wind turbines, especially for turbines with DFIGs, is their operation during grid faults. Faults in the power system, even far away from the location of the turbine, can cause a voltage dip at the connection point of the wind turbine. The dip in the grid voltage will result in an increase of the current in the stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, this current will also flow in the rotor circuit and the power-electronic converter. This can lead to the destruction of the converter. It is possible to try to limit the current by current-control on the rotor side of the converter; however, this will lead to high voltages at the converter terminals, which might also lead to the destruction of the converter.

A possible solution that is sometimes used, is to short circuit the rotor windings of the generator with so-called crowbars. Resuming normal operation without transients when the fault is cleared is not properly feasible with this solution, however. Most

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The authors are with the Electrical Power Processing Group of the Delft University of Technology, Delft 2628CD, The Netherlands (e-mail: J.Morren@its.tudelft.nl).
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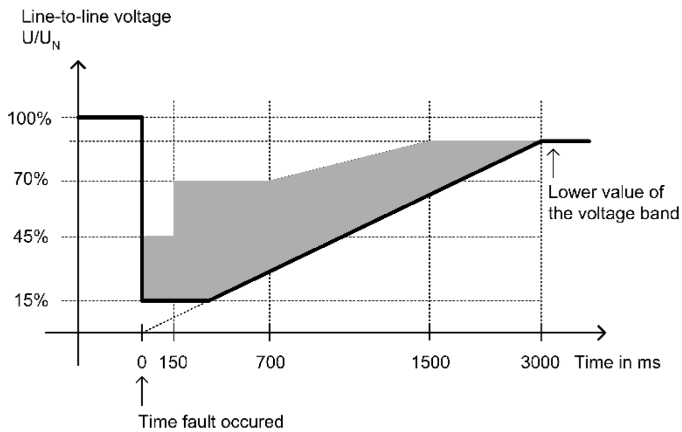

Fig. 2. E.On Netz requirements for wind park behavior during faults.

turbines using DFIGs therefore are automatically disconnected from the grid nowadays, when such a fault occurs [3].

Worldwide, there is an ambition to install a large amount of wind power and to increase the share of energy consumption that is produced by wind turbines. The interaction with the grid becomes increasingly important then [4]. This can be understood as follows. When all wind turbines would be disconnected in case of a grid failure, these renewable generators will—unlike conventional power plants—not be able to support the voltage and the frequency of the grid during and immediately following the grid failure. This would cause major problems for the systems stability [5]. It is therefore worldwide recognized that to enable large-scale application of wind energy without compromising system stability, the turbines should stay connected to the grid in case of a failure. They should—similar to conventional power plants—supply active and reactive power for frequency and voltage support immediately after the fault has been cleared, which is normally within a fraction of a second.

In Northern Germany, where the concentration of wind turbines is high, the grid operator (E.On Netz) already has set requirements for the behavior of wind turbines. Instead of disconnecting them from the grid, the turbines should be able to follow the characteristic shown in Fig. 2. Only when the grid voltage goes below the curve (in duration or voltage level), the turbine is allowed to disconnect. When the voltage is in the gray area, the turbine should supply reactive power.

The behavior during grid faults has already been studied for different types of turbines [6], [7]. When it is not possible to keep DFIGs connected to the grid, large-scale introduction of DFIG turbines does not seem feasible.

In this paper, a method is proposed that makes it possible for wind turbines using DFIGs to stay connected to the grid during grid faults. The key of the solution is to limit the high current in the rotor and to provide a bypass for it via a set of resistors that are connected to the rotor windings. With these resistors, it is possible to survive grid faults without disconnection of the turbine from the grid. Because the generator and converter stay connected, the synchronism of operation remains established during and after the fault and normal operation can be continued immediately after the fault has been cleared. A control strategy has been developed that takes care of the transition back to normal operation. Without this transition control, large transients would occur.

When the dip duration is longer than a few hundred milliseconds, the short-circuit resistors can be disconnected and the system can resume normal operation at reduced grid voltage. It can even supply reactive power to the grid during the fault.

Recently, some papers have been published that discuss the protection of DFIGs during grid disturbances [8]–[10]. However, most papers give little information on the way the protection scheme is implemented. Further, they give only limited information on the behavior of the rotor voltage and current during disturbances, while these signals are important during disturbances. Rotor currents or voltages that are too high might destruct the converter in the rotor circuit. In this paper, the focus is on the rotor-side signals of the DFIG. Further, this paper is the first that also discusses the possibility to supply reactive power to the grid during faults in order to support voltage restoration.

First, shortly, some information is given on the modeling of the system. Then, the controller is described. After a short discussion of voltage dips, simulation results are presented that show the effectiveness of the protection scheme. The paper finishes with a discussion of the results and a conclusion and recommendations for further research on this topic.

II. Modeling of the DFIG

A large number of papers describe the modeling of DFIGs [11]–[14]. Only the most important aspects of the modeling will be presented here. The system has been modeled and simulated in the Simulink toolbox extension of Matlab.

A $d-q$ reference frame is chosen to model the DFIG. The model of the induction machine is based on the fifth-order two-axis representation commonly known as the "Park model." A synchronously rotating $d-q$ reference frame is used with the direct d-axis oriented along the stator flux position. In this way, decoupled control between the electrical torque and the rotor excitation current is obtained. The reference frame is rotating with the same speed as the stator voltage. When modeling the DFIG, the generator convention will be used, which means that the currents are outputs and that real power and reactive power have a positive sign when they are fed into the grid. Using the generator convention, the following set of equations results:

$$\begin{aligned} v_{ds} &= -R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \\ v_{qs} &= -R_s i_{qs} + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \\ v_{dr} &= -R_r i_{dr} - \omega_r \psi_{qr} + \frac{d\psi_{dr}}{dt} \\ v_{qr} &= -R_r i_{qr} + \omega_r \psi_{dr} + \frac{d\psi_{qr}}{dt} \end{aligned} \tag{1}$$

with v being the voltage (V), R is the resistance [Ω], i is the current (A), ω_s and ω_r are the stator and rotor electrical angular velocity (rad/s), respectively, and ψ is the flux linkage (Vs). The indices d and q indicate the direct and quadrature axis components of the reference frame and s and r indicate stator and rotor quantities, respectively. All quantities in (1) are functions of time.

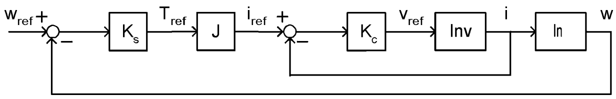

Fig. 3. Cascade control for rotor speed.

A converter is used to connect the rotor circuit of the DFIG to the grid, whereas the stator circuit is connected to the grid directly. The converter must be able to transfer energy in both directions. The grid-side converter has to control the dc-link voltage, regardless of the magnitude and direction of the rotor power and the rotor-side converter has to control the rotor currents.

For the converter model, it is assumed that the converters are ideal. They exactly make the reference voltage signal that is set by the controller. It has been shown in [13] that such a model gives good simulation results for the simulation of voltage dips.

III. Controller

The electrical and mechanical dynamics of a wind turbine are in different time scales. The electrical dynamics are much faster than the mechanical ones. Therefore, it is possible to control the machine in a cascade structure as shown in Fig. 3. The fast electrical dynamics can be controlled in an inner loop and a speed controller can be added in a much slower outer loop.

Due to the chosen orientation of the reference frame, the active and reactive power control are decoupled. The active and reactive power of the DFIG can be controlled by the q- and the d-axis component of the rotor current, respectively. The voltage equations of the rotor are given in (1). Since for small values of R_s the stator flux is mainly determined by the stator voltage, it is practically constant. This implies that the derivative of the stator flux is close to zero and can be neglected [11]. The rotor voltage equations of (1) can then be written as [12]

$$\begin{aligned} v_{dr} &= -R_r i_{dr} - L_r \frac{di_{dr}}{dt} - \omega_r \psi_{qr} \\ v_{qr} &= -R_r i_{qr} - L_r \frac{di_{qr}}{dt} + \omega_r \psi_{dr}. \end{aligned} \tag{2}$$

The last term in both equations represents a cross-relation between the two current components. Reference voltages to obtain the desired currents can be written as [12]

$$\begin{aligned} v_{dr}^* &= v_{dr}' - \omega_r \psi_{qr} \\ v_{qr}^* &= v_{qr}' + \omega_r \psi_{dr} \end{aligned} \tag{3}$$

with

$$\begin{aligned} v_{dr}' &= -R_r i_{dr} - L_r \frac{di_{dr}}{dt} \\ v_{qr}' &= -R_r i_{qr} - L_r \frac{di_{qr}}{dt}. \end{aligned} \tag{4}$$

The i_{dr} and i_{qr} errors are processed by a PI controller to give v_{dr} and v_{qr}, respectively. To ensure good tracking of these currents, the cross-related flux terms are added to v_{dr} and v_{qr} to obtain the reference voltages.

The internal-model-control (IMC) principle [15] has been used to design the controllers. For a first-order system, the controller becomes a proportional-integral (PI) controller [16]

$$C(s) = k_p + \frac{k_i}{s} = \frac{\alpha}{s} G^{-1}(s) \tag{5}$$

where k_p is the proportional gain and k_i is the integral gain. Treating $\omega_r \Psi_{dr}$ and $\omega_r \Psi_{qr}$ in (3) as a disturbance, the transfer function from the rotor voltage v_{dr}' to the rotor current i_{dr} and from the rotor voltage v_{qr}' to the rotor current i_{qr} is given by

$$G(s) = \frac{1}{L_r s + R_r}. \tag{6}$$

Using the IMC principle, the current controllers become

$$C(s) = k_p + \frac{k_i}{s} = \frac{\alpha_c}{s} G^{-1}(s) \tag{7}$$

where α_c is the bandwidth of the current control loop, k_p is the proportional gain, and k_i is the integral gain. The two gains become [11]

$$k_p = \alpha_c L_r \quad k_i = \alpha_c R_r. \tag{8}$$

The rotational speed is given by

$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_m - T_e). \tag{9}$$

It is assumed that the current controller is much faster than the speed controller. The electrical torque is then $T_e = T_{e,\text{ref}}$. The reference torque is set to

$$T_{e,\text{ref}} = T_{e,\text{ref}'} - B_a \omega_m \tag{10}$$

where B_a is an "active damping torque" [11]. The transfer function from rotational speed to electrical torque becomes

$$G_s(s) = \frac{1}{Js + B_a}. \tag{11}$$

Using again the internal model control method, the following gains of the controller are obtained:

$$k_{ps} = \alpha_s J \quad k_{is} = \alpha_s B_a \tag{12}$$

where α_s is the desired closed-loop bandwidth of the speed controller. When B_a is chosen to be $B_a = J\alpha_s$, changes in the mechanical torque are damped with the same time constant as the bandwidth of the speed control loop [11]. The d-axis rotor current directly controls the reactive power of the stator.

IV. Voltage Dip Behavior of DFIG Without Protection

A voltage dip (also the word voltage sag is used) is a sudden reduction (between 10% and 90%) of the voltage at a point in the electrical system, which lasts for half a cycle to 1 min [17]. There can be many causes for a voltage dip: short circuits somewhere in the grid, switching operations associated with a temporary disconnection of a supply, the flow of the heavy currents that are caused by the start of large motor loads, or large currents drawn by arc furnaces or by transformer saturation. Voltage dips

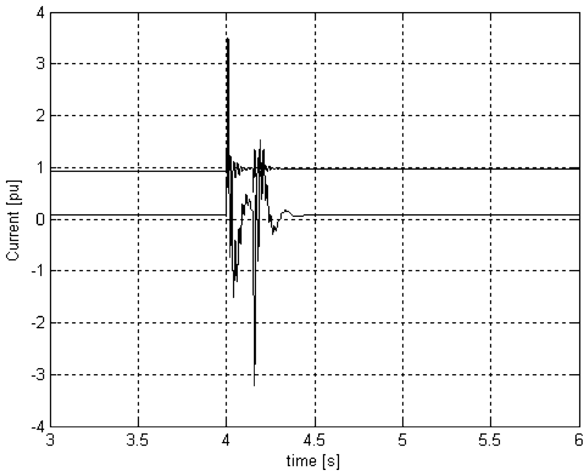

Fig. 4. Rotor currents i_d (bottom) and i_q (top) for a voltage dip of 85%, 0.2 s without protection.

due to short-circuit faults cause the majority of equipment trips [18] and are therefore of most interest. Faults are either symmetrical (three-phase or three phase-to-ground faults) or nonsymmetrical (single-phase or double-phase or double-phase-to-ground faults). Depending on the type of fault, the magnitudes of the voltage dips of each phase might be equal (symmetrical fault) or unequal (nonsymmetrical faults). The magnitude of a voltage dip at a certain point in the system depends mainly on the type of the fault, the distance to the fault, the system configuration, and the fault impedance.

The dynamics of the DFIG have two poorly damped poles in the transfer function of the machine, with an oscillation frequency close to the line frequency. These poles will cause oscillations in the flux if the doubly-fed induction machine is exposed to a grid disturbance [11]. After such a disturbance, an increased rotor voltage will be needed to control the rotor currents. When this required voltage exceeds the voltage limit of the converter, it is not possible any longer to control the current as desired.

This implies that a voltage dip can cause high induced voltages or currents in the rotor circuit. The high currents might destroy the converter, if nothing is done to protect it. In Fig. 4, the rotor currents of the machine are shown for a voltage dip of 85%, implying, that only 15% of the grid voltage remains. The d-axis and q-axis component of the rotor current are shown in the figure. It can be seen that the rotor currents oscillates to about four times the rated current. If nothing is done to protect the converter, it will be destroyed completely.

V. Voltage Dip Behavior of DFIG With Protection

In this section, a description will be given of a technique that has the objective to keep the generator connected to the grid in case of a grid failure. With this technique, the turbine can resume power generation after clearance of the fault within a few hundred milliseconds. It is assumed that the DFIG is part of an offshore wind farm and that the voltage dip occurs somewhere in the 150-kV transmission grid. The DFIG is connected to this grid through two transformers and a cable as shown in Fig. 5. The 960-V stator voltage of the DFIG is first transformed to 34 kV, the rated voltage of the cable. Afterwards, it is transformed to 150 kV. Data of a 2.5-MW wind turbine with a DFIG have been used during the simulations. The machine parameters, as well as the controller parameters, can be found in the Appendix.

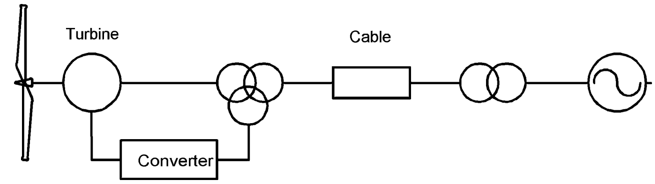

Fig. 5. Simulation model setup.

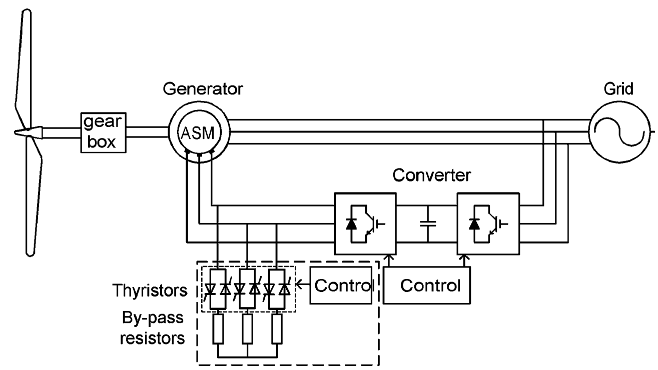

Fig. 6. DFIG bypass resistors in the rotor circuit.

The key of the protection technique is to limit the high currents and to provide a bypass for it in the rotor circuit via a set of resistors that are connected to the rotor windings (Fig. 6). This should be done without disconnecting the converter from the rotor or from the grid. Thyristors can be used to connect the resistors to the rotor circuit. Because the generator and converter stay connected, the synchronism of operation remains established during and after the fault. The impedance of the bypass resistors is of importance but not critical. They should be sufficiently low to avoid too large of a voltage on the converter terminals. On the other hand, they should be high enough to limit the current. A range of values can be found that satisfies both conditions. In the simulation, a value of 0.86 p.u. was applied. When the fault in the grid is cleared, the wind turbine is still connected to the grid. The resistors can be disconnected by inhibiting the gating signals and the generator resumes normal operation. A control strategy has been developed that takes care of the transition to normal operation. Without special control action, large transients would occur.

In order to show the effectiveness of the protection scheme, the behavior of the DFIG during a voltage dip of 85% (15% remaining voltage) and 200 ms is simulated. This dip could, for example, be caused by a short circuit somewhere in the grid. The resulting stator voltage is shown in Fig. 7.

In Fig. 4, the rotor current was shown for a voltage dip in a case without protection. The same rotor current, but now with protection, is shown in Fig. 8.

Whereas the rotor current without protection oscillates to about four times the nominal current, it now only becomes slightly higher than the nominal current. This current is not flowing through the converter, but through the short-circuit resistances. For the rotor of the generator, it is allowable that the current becomes slightly higher than the nominal current for a short time. The rotor has a sufficiently large thermal time

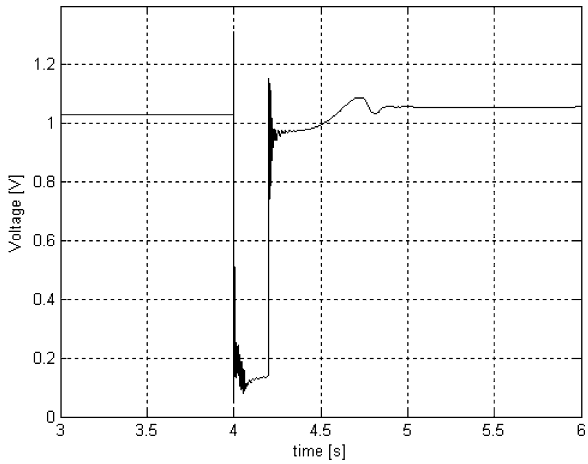

Fig. 7. Stator voltage for a voltage dip of 85%, 0.2 s.

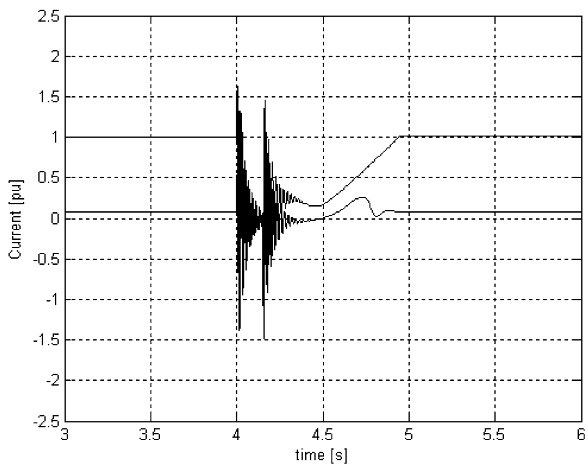

Fig. 8. Rotor currents i_d (bottom) and i_q (top) for a voltage dip of 85%, 0.2 s with protection.

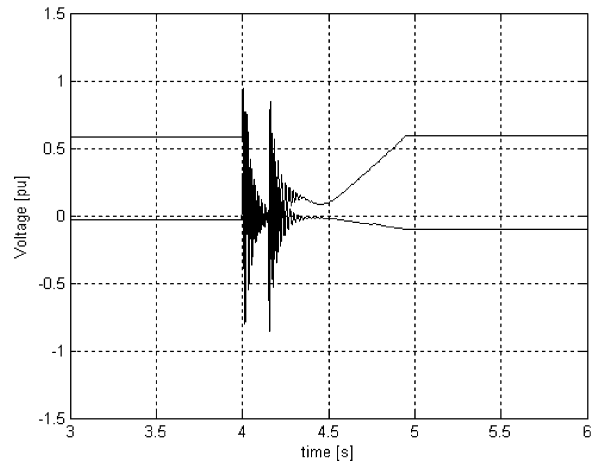

Fig. 9. Rotor voltages v_d (bottom) and v_q (top) for a voltage dip of 85%, 0.2 s with protection.

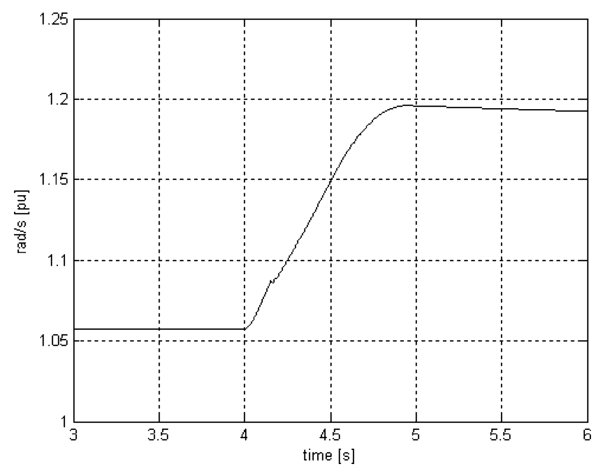

Fig. 10. Mechanical speed for a voltage dip of 85%, 0.2 s with protection.

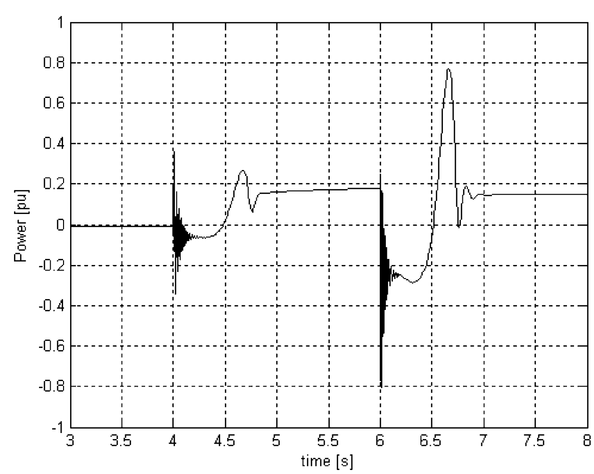

Fig. 11. Reactive power supply for a voltage dip of 40%, 2 s with protection.

constant to cope with these currents. The voltage across the short-circuit resistors and, thus, the voltage across the rotor and converter terminals is shown in Fig. 9. The d-axis and q-axis components of the voltage are shown. It can be seen that the voltage remains below the rated voltage.

When the whole turbine would be disconnected from the grid, it can become difficult to control the mechanical rotation of the wind turbine, as it is not possible any longer to develop an electrical torque to counteract the mechanical torque provided by the wind power. With the bypass resistors connected to the rotor, the turbine stays connected to the grid, and it is still possible to develop an electrical torque. The rotational speed of the turbine during the dip is shown in Fig. 10.

When the dip is cleared, the wind turbine should resume normal operation. Special control action should be taken, however, because otherwise large transients can occur. These transients occur when the current controllers resume their operation without taking into account the occurrence of the dip. Due to the mismatch between the signals that are expected by the controllers and the real signals, windup of the integrators will occur, resulting in large transients when normal operation is resumed. In order to prevent these transients, a soft transition to normal operation should be made. To get this transition, the reference values are set to the actual values of the currents at the moment the fault is cleared. The reference values are then slowly changed to the reference values that are needed to obtain the required behavior of the turbine.

When the dip holds on for a longer time, it can be required that the generator supplies reactive power. The proposed protection scheme also offers the possibility to supply reactive power during the dip and immediately after the dip as shown in Fig. 11.

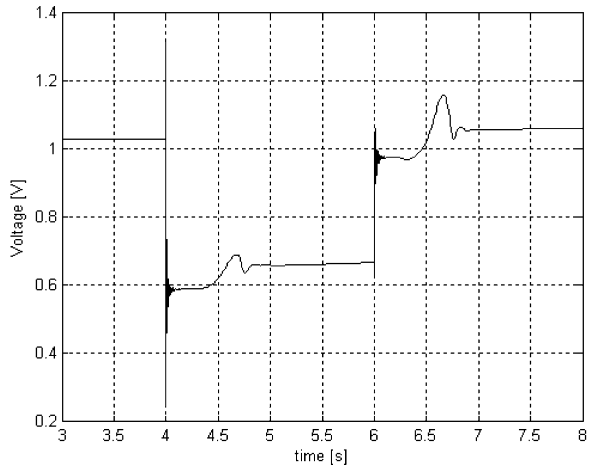

Fig. 12. Stator voltage for a voltage dip of 40%, 2 s.

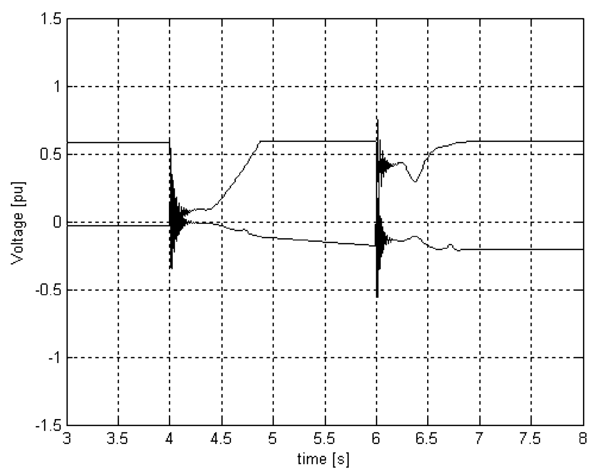

Fig. 13. Rotor voltages v_d (bottom) and v_q (top) for a voltage dip of 40%, 2 s with protection.

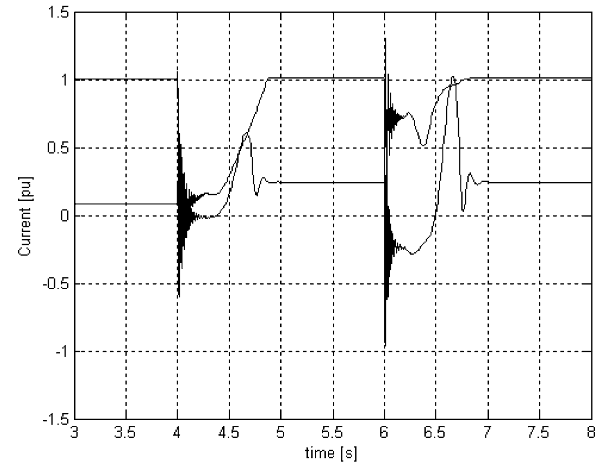

Fig. 14. Rotor currents i_d (bottom) and i_q (top) for a voltage dip of 40%, 2 s with protection.

Apart from the transients, the turbine is generating about 0.2-p.u. reactive power during and after the fault. At the moment the dip occurs, the short-circuit resistors are switched on. When the oscillations have damped out and the rotor currents are below the rated current, the resistors can be switched off and the converter is still connected to the rotor. As long as the grid-side converter is able to control the dc-link voltage of the converter, the rotor-side converter can still control u_{dr} and u_{qr} at the rotor terminals. By controlling u_{dr}, the reactive power to the grid can be controlled in the same way as reactive power control is realized during normal operation. The root-mean-square (rms) stator voltage is shown in Fig. 12. The d-axis and q-axis components of the rotor voltage and rotor current during the reactive power–supply operation are shown in Figs. 13 and 14, respectively. It can be seen that they stay below their rated values, apart from some peaks during the transients.

VI. Discussion

The results that have been obtained are based on simulations. Two types of errors are introduced by simulation; first, the simulation models are approximations of reality and, second, the models are evaluated with numerical methods, which introduce calculation errors. The most important modeling assumption that has been made concerns the converter model in which the actual switching has not been modeled. It has been shown in [13], however, that the reduced converter model can be used during voltage dip simulations. Simulink uses numerical integration methods to solve the differential equations. This can introduce round-off and truncation errors. Due to the round-off errors, values can be slightly different, but it will have no noteworthy impact on the total system behavior. The difference between the exact solution and the calculated solution is dominated by the truncation error [19]. The ode23tb variable step-size solver of Matlab has been used to perform the simulations. This solver is an implementation of an implicit Runge–Kutta formula. The time-step selection is based on the local truncation error. Therefore, this error will be limited [19].

A basic proof of principle of the protection scheme for a DFIG has been given in this paper. Further research should be done to optimize the solution. Especially the oscillations in the currents after occurrence and clearance of the fault are important. The oscillations are due to poorly damped flux poles. In [11], control techniques are described that can be used for damping of these flux oscillations. For small voltage dips, this solution can be used and using the short-circuit resistors will not be necessary. For larger voltage dips, the short-circuit resistors should still be used, however.

It has been shown in [20] that when the d-component of the rotor current exceeds a certain value, the system becomes unstable. The reactive power supply is controlled by the d-component of the rotor current. Careful attention should therefore be paid to the stability, with regard to reactive power supply during grid disturbances.

During a dip, the electromagnetic torque that can be made by the machine is limited. It might therefore become difficult to control the wind rotor when the dip is too long. Combined control with a pitch controller of the wind turbine should be investigated.

VII. Conclusion

In this paper, a technique is described which has the objective to keep the generator connected to the grid in case of a grid failure so that it can resume power generation after clearance of the fault in the grid. The key of the technique is to limit the high currents and to provide a bypass for it in the rotor circuit via a set of resistors that are connected to the rotor windings without disconnecting the converter from the rotor or from the grid. The wind turbine can resume normal operation within a few hundred milliseconds after the fault has been cleared. For longer voltage dips, the generator can even supply reactive power to the grid. Simulation results show the effectiveness of the proposed technique.

APPENDIX

The machine and controller parameters that have been used during the simulations are given below.

Machine parameters
apparent power $S_{\text{nom}} = 2.5$ MW;
mutual inductance $L_m = 2.5$ p.u.;
stator leakage inductance $L_s = 0.11$ p.u.;
rotor leakage inductance $L_r = 0.07$ p.u.;
stator resistance $R_s = 0.0021$ p.u.;
rotor resistance $R_r = 0.0021$ p.u.;
pole number $p = 3$;
inertia $J = 240\ \text{kg} \cdot \text{m2}$;
bypass resistor $R_{bp} = 0.86$ p.u.
Controller parameters
$k_p = 2, k_i = 32, k_{ps} = 25, k_{is} = 155.$

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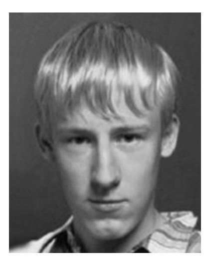

Johan Morren (S'03) received the M.Sc. degree in electrical engineering in 2000 from the Delft University of Technology, Delft, The Netherlands, where he is currently pursuing the Ph.D. degree on grid integration of distributed generators.

Currently, he is a Research Assistant in the Electrical Power Processing Group of the Delft University of Technology. He worked on projects regarding the grid connection of renewable energy sources and a project regarding the sterilization of liquid foods with pulsed electric fields (PEF).

Sjoerd W. H. de Haan (M'99) received the M.Sc. degree in applied physics from the Delft University of Technology, Delft, The Netherlands, in 1975.

Currently, he is Associate Professor of Power Electronics at the Delft University of Technology, where he has been since 1995. His research covers electric systems for renewable energy sources and pulsed power supplies for various applications.