Short-Circuit Current of Wind Turbines With Doubly Fed Induction Generator

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

***Abstract*—The short-circuit current contribution of wind turbines has not received much attention so far. This paper considers the short-circuit behavior, especially the short-circuit current of wind turbines with a doubly fed induction generator. Mostly, these wind turbines have a crowbar to protect the power electronic converter that is connected to the rotor windings of the induction generator. First, the maximum value of the short-circuit current of a conventional induction machine is determined. The differences between a crowbar-protected doubly fed induction generator and a conventional induction generator are highlighted and approximate equations for the maximum short-circuit current of a doubly fed induction generator are determined. The values obtained in this way are compared to the values obtained from time domain simulations. The differences are less then 15%.**

***Index Terms*—AC generators, protection, short circuit currents, wind power generation.**

NOMENCLATURE

Symbols

f	Frequency [Hz].
i	Current [A].
I	Effective phase current [A].
k	Coupling factor [-].
L	Inductance [H].
R	Resistance [Ω].
t	Time [s].
T	Time constant [s].
v	Voltage [V].
V	Effective phase voltage [V].
X	Reactance [Ω].
Z	Impedance [Ω].
α	Angle [rad].
σ	Leakage factor [-].
ω	Angular velocity [rad/s].
ψ, Ψ	Flux [T].

Subscripts

a	Phase a.
cb	Crowbar.
m	Mutual.
max	Maximum.
r	Rotor.
s	Stator.
σ	Leakage.

Manuscript received July 12, 2006; revised October 23, 2006. This work was supported by SenterNovem within the Program IOP-EMVT. Paper no. TEC-280-2006.

The authors are with the Electrical Power Processing Unit, Delft University of Technology, 2628CD Delft, The Netherlands (e-mail: JohanMorren@ieee.org; S.W.H.deHaan@tudelft.nl).

Digital Object Identifier 10.1109/TEC.2006.889615

I. INTRODUCTION

THE NUMBER of wind turbines connected to the grid is steadily increasing. The interaction between wind turbine and grid has been investigated extensively in recent times [1]–[4]. One issue that did not receive much attention so far is the contribution of wind turbines to short-circuit current. The short-current contribution is important to know with respect to the coordination of network protection, and the maximum currents that are allowed in a network [5], [6].

For variable-speed wind turbines with a power electronic converter between the stator and the grid, the short-circuit current can be determined relatively easily. It is determined by the converter and will generally not exceed the nominal current of the converter [7]. The other two main types of wind turbines are constant-speed wind turbine and a variable-speed wind turbine with doubly fed induction generator (DFIG); both have an induction machine directly coupled to the grid. The short-circuit behavior of induction machines is strongly dependent on the machine characteristics. It has received considerable attention in the past and some good approximate equations to determine the maximum short-circuit current have been derived [8].

A DFIG is also directly coupled to the grid but it has a power electronic converter connected between the rotor windings of the induction machine and the grid. It needs to have a provision to protect the converter during short circuits [9]. The voltage drop at the terminals will result in large, oscillatory currents in the stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, these currents will also flow in the rotor circuit and through the PEC [10], [11]. The high currents can cause thermal breakdown of the converter. Most protection schemes that have been proposed are based on a so-called crowbar [9], [10], [12], [13]. During a fault, the rotor windings are short-circuited by a set of resistors. The short-circuit current will flow through this crowbar instead of the converter. A number of papers discuss the protection of DFIG-based wind turbines, but no detailed analysis, investigation, and explanation of the behavior has yet been published.

This paper analyses the behavior of a crowbar-protected DFIG. Based on this analysis, approximate equations are derived that can be used to determine the short-circuit current contribution of the turbine. A worst case is considered in which a short circuit occurs at the terminals of the induction machine. This will give the maximum value that the short-circuit current can reach. This paper is a continuation of the preliminary investigation into the protection of DFIG-based wind turbines presented in [9]. The current paper focuses on the mathematical analysis of the fault behavior and the short-circuit current that is supplied.

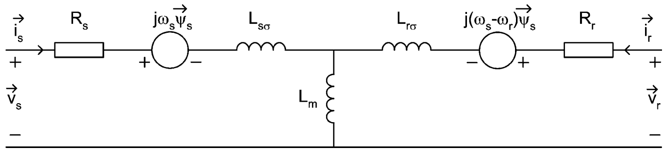

Fig. 1. Equivalent circuit of induction machine for transient analysis.

First, the fault-behavior of a conventional induction machine is considered. The next two sections discuss the protection of a DFIG and investigate how the maximum short-circuit current of the DFIG can be determined. A number of cases are studied in which, for three different generators, the calculated values are compared with the results of time domain simulations.

II. Induction Machine Response to Fault

This section determines the response of an induction machine to a symmetrical short circuit at its stator terminals. The analysis is based on [8]. For the analysis, a space vector description is used. In a synchronously rotating reference frame, the equations describing an induction machine are [8]

$$\vec{v}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} + j\omega_s \vec{\psi}_s \tag{1}$$

$$\vec{v}_r = R_r \vec{i}_r + \frac{d\,\vec{\psi}_r}{dt} + j(\omega_s - \omega_r)\vec{\psi}_r \tag{2}$$

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r \tag{3}$$

$$\vec{\psi}_r = L_m \vec{i}_s + L_r \vec{i}_r\ . \tag{4}$$

In these equations, all parameters are reduced to the stator side. Based on these equations, the equivalent circuit of the induction machine that is shown in Fig. 1 can be obtained. It can be used for transient analysis of an induction machine.

Based on (3) and (4), the currents can be written as a function of the fluxes as

$$\vec{i}_s = \frac{1}{L_s - \frac{L_m^2}{L_r}} \vec{\psi}_s - \frac{L_m}{L_r} \frac{1}{L_s - \frac{L_m^2}{L_r}} \vec{\psi}_r \tag{5}$$

$$\vec{i}_r = -\frac{L_m}{L_s} \frac{1}{L_r - \frac{L_m^2}{L_s}} \vec{\psi}_s + \frac{1}{L_r - \frac{L_m^2}{L_s}} \vec{\psi}_r\ . \tag{6}$$

In these equations, the term $L_s - (L_m^2/L_s)$ is similar to the transient inductance of a synchronous machine [8]. It will be denoted as L'_s. Knowing that $L_s = L_{s\sigma} + L_m$ and $L_r = L_{r\sigma} + L_m$, the transient stator inductance can be written as

$$L'_s = L_{s\sigma} + \frac{L_{r\sigma} L_m}{L_{r\sigma} + L_m}. \tag{7}$$

Similarly, the transient rotor inductance can be introduced as

$$L'_r = L_{r\sigma} + \frac{L_{s\sigma} L_m}{L_{s\sigma} + L_m}. \tag{8}$$

The equations can further be simplified by introducing the stator and rotor coupling factors as

$$k_s = \frac{L_m}{L_s} \tag{9}$$

$$k_r = \frac{L_m}{L_r} \tag{10}$$

and the leakage factor

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}. \tag{11}$$

With the inductances and factors, (5) and (6) become

$$\vec{i}_s = \frac{\vec{\psi}_s}{L'_s} - k_r \frac{\vec{\psi}_r}{L'_s} \tag{12}$$

$$\vec{i}_r = -k_s \frac{\vec{\psi}_s}{L'_r} + \frac{\vec{\psi}_r}{L'_r}. \tag{13}$$

The equations that have been obtained so far will be used to derive an approximate equation for the maximum short-circuit current supplied by an induction machine. The rotational speed of the rotor of an induction machine differs by only a few percent from the grid frequency and is assumed to stay constant during a transient event. This introduces only a limited error [8].

The voltage equations of an induction machine are given by (1) and (2). Solving these differential equations will give a particular solution, which give the current in a steady-state situation. The general solution can be obtained by adding the solution of the homogeneous differential equation to the steady-state currents. The solution of the homogeneous equation gives the "free currents," which separately satisfy the homogenous differential equation. The solution of the homogeneous equation can be obtained by setting the stator and rotor voltage to zero.

During the occurrence of a short circuit, the currents go from the original stationary state to a new stationary state. The continuity of the transition is assured by the "free currents." The "free currents" that occur during this compensation process can be investigated separately from the stationary currents, as if both stator and rotor are short circuited. [8] The "free currents" of an induction machine that rotates almost synchronously are similar to those in a synchronous machine. During the transition from one stationary state to another the following currents are present in the induction machine.

- *Stationary currents:* This current has a frequency of f_s (stator) and $f_r = s \cdot f_s$ (rotor).
- *Stator dc current:* It can be considered as a space vector with a fixed position. As the rotor rotates with $\omega_m = (1-s)\omega_s$ (assuming one pole pair) with respect to this fixed space vector, the rotor adds an alternating current with $f = (1-s)\omega_s$ to this dc current.
- *Rotor dc current:* This current rotates with the rotor and creates the alternating current in the stator.

The dc components are no real dc currents. In reality, the space vector rotates slowly and is damped exponentially. The space vector rotates faster for a larger stator and rotor resistance. The time constant for the damping of the dc components in stator and rotor are given by [8]

$$T_{s'} = \frac{L_{s'}}{R_s} \tag{14}$$

$$T_{r'} = \frac{L_{r'}}{R_r}. \tag{15}$$

The currents and fluxes in the machine during a short circuit are determined in two steps. In the first step, the stator and rotor resistance are neglected. The current components and flux components that are obtained are considered as the start values. In the next step, the components are multiplied by a damping factor, which is based on the resistance and leakage inductance of the machine. The results that are obtained in this way have an error of 10%–20% [8].

The short-circuit current of an idle running machine will be determined. Neglecting the mechanical losses, the machine rotates at the synchronous rotational speed ω_s. The stator resistance can be neglected in steady state. Before the occurrence of the short circuit, the rotor current is zero: $I_r = 0$. The stator current is

$$I_s e^{j\omega_s t} = \frac{V_s e^{j\omega_s t}}{jX_s} = \frac{V_s e^{j\omega_s t}}{j\omega_s L_s}. \tag{16}$$

The stator flux is

$$\Psi_s e^{j\omega_s t} = I_s e^{j\omega_s t} L_s = \frac{V_s e^{j\omega_s t}}{j\omega_s}. \tag{17}$$

The rotor flux (in a fixed reference frame) is

$$\Psi_r e^{j\omega_s t} = I_s e^{j\omega_s t} L_m = \frac{L_m}{L_s}\frac{V_s e^{j\omega_s t}}{j\omega_s} = k_s \frac{V_s e^{j\omega_s t}}{j\omega_s}. \tag{18}$$

At time $t = 0$, a three-phase short circuit is assumed to occur at the stator of the machine. Both the rotor and the stator are then short circuited. This implies that the flux in both the windings does not change. The stator flux is given by

$$\psi_s = \Psi_{s,0} = \frac{\sqrt{2}V_s}{j\omega_s}. \tag{19}$$

The rotor flux has to stay fixed to the rotor winding. As the rotor rotates synchronously with the angular velocity ω_s, the rotor flux ψ_r also rotates with that angular velocity, as shown in Fig. 2. In a fixed reference frame, the rotor flux is thus given by

$$\psi_r = \Psi_{r,0} = k_s \frac{\sqrt{2}V_s}{j\omega_s} e^{j\omega_s t}. \tag{20}$$

At the moment when the short circuit occurs, the rotor and stator flux ψ_r and ψ_s have the same angle and approximately the same amplitude. The stator flux is fixed to the stator, but the rotor flux will change with the rotor and after half a period, it will be 180° out of phase and have an opposite direction. The currents in the machine will then reach their maximum value. They can become very high and are only limited by the leakage inductances.

The stator short-circuit current can be obtained by substituting (19) and (20) in (12) as

$$\vec{i}_s = \frac{\vec{\psi}_s}{L'_s} - k_r \frac{\vec{\psi}_r}{L'_s} = \frac{\vec{\psi}_s - k_r \vec{\psi}_r}{L'_s} = \frac{\sqrt{2}V_s}{j\omega_s L'_s}\left[1 - k_r k_s e^{j\omega_s t}\right]. \tag{21}$$

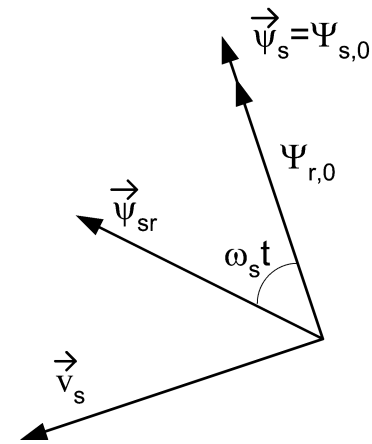

Fig. 2. Induction machine flux vectors during a three-phase short circuit (with resistance neglected).

Writing $k_r k_s$ as $1-\sigma$ [see (9)–(11)], the equation becomes

$$\vec{i}_s = \frac{\sqrt{2}V_s}{j\omega_s L'_s}\left[1 - (1-\sigma)e^{j\omega_s t}\right]. \tag{22}$$

This equation is obtained under the assumption that the stator and rotor resistance can be neglected, implying that the current is undamped. In reality, the current will always decline.

The first term inside the rectangular brackets of (22) represents the dc component in the stator current. This current will be damped with the transient time constant T'_s. The second term represents the ac component in the stator current, to which a dc component in the rotor current belongs. It will thus be damped with the transient time constant T'_r. Taking into account these two damping factors, (22) becomes [8]

$$\vec{i}_s = \frac{\sqrt{2}V_s}{jX'_s}\left[e^{-t/T'_s} - (1-\sigma)e^{j\omega_s t}e^{-t/T'_r}\right]. \tag{23}$$

When the voltage v_s has an angle $\alpha + (\pi/2)$ with respect to stator phase a at the moment that the short circuit occurs, then $v_s = j\sqrt{2}V_s e^{j\alpha}$. The short-circuit current in this phase is then the projection of the vector i_s on the a-phase, i.e., its real part

$$i_{sa} = \frac{\sqrt{2}V_s}{X'_s}\left[e^{-t/T'_s}\cos\alpha - (1-\sigma)e^{j\omega_s t}e^{-t/T'_r}\cos(\omega_s t + \alpha)\right]. \tag{24}$$

The current is shown in Fig. 3.

Although the current vector does not reach the maximum value exactly at $t = T/2$, the current after half a period gives a good approximation of the maximum current [8]. The maximum current can thus be obtained by substituting $t = T/2$ in (23) as

$$i_{s,\max} = \frac{\sqrt{2}V_s}{X'_s}\left[e^{-T/2T'_s} + (1-\sigma)e^{-T/2T'_r}\right]. \tag{25}$$

III. DFIG Protection

This section describes the short-circuit behavior of doubly fed induction generators and the crowbar protection that is applied to protect the generators.

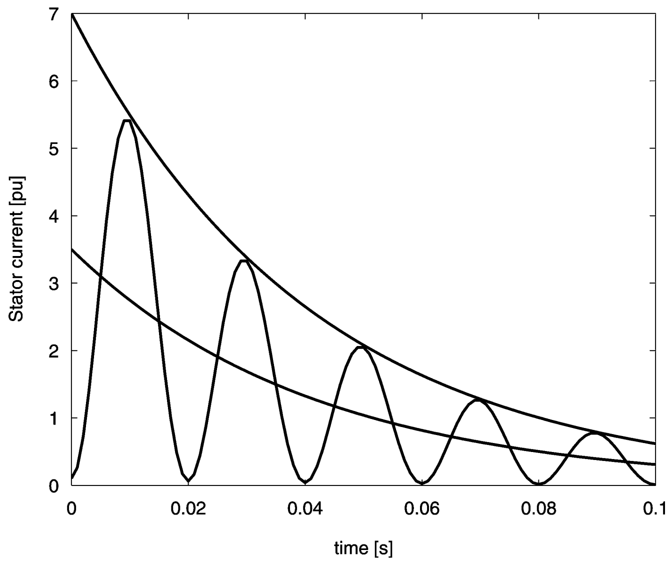

Fig. 3. Short-circuit current in one phase of an induction machine.

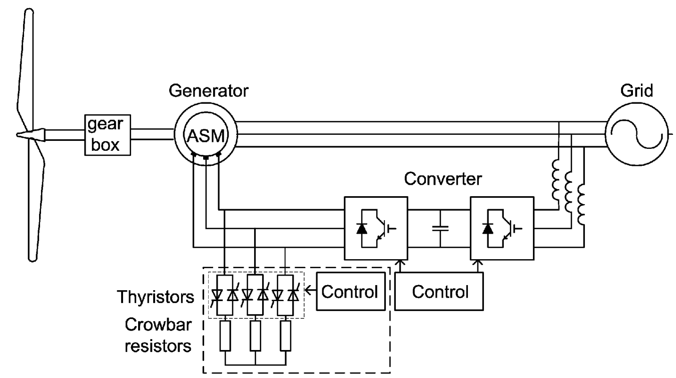

Fig. 4. DFIG crowbar resistors in the rotor circuit.

The stator voltage equation of the induction machine is given in (1). In normal operation, the space vectors rotate at a synchronous speed with respect to the reference frame. Ignoring the stator resistance, the derivative of the stator flux is directly proportional to the grid voltage. When the voltage drops to zero (in case of a fault at the generator terminals), the stator flux space vector stops rotating. This produces a dc component in the stator flux. The dc component in the rotor flux of the machine is fixed to the rotor and will continue rotating. This will thus add an alternating component to the dc component of the stator flux. The maximum value that the currents reach depends mainly on the stator and rotor leakage inductance. The speed at which the dc component will decay is mainly determined by the transient time constants of the stator and rotor, which is given by (14) and (15).

The voltage dip will cause large (oscillating) currents in the rotor circuit of the DFIG to which the power electronic converter is connected. A high rotor voltage will be needed to control the rotor current. When this required voltage exceeds the maximum voltage of the converter, it is not possible any longer to control the current as desired. This implies that large currents can flow, which can destroy the converter.

In order to avoid breakdown of the converter switches, a crowbar is connected to the rotor circuit. This can, for example, be done by connecting a set of resistors to the rotor winding via bi-directional thyristors as is shown in Fig. 4. When the rotor currents become too high, the thyristors are fired and the high currents do not flow through the converter but rather into the crowbar resistors.

The enabling of the crowbar can be followed by different actions. The whole wind turbine can be disconnected from the grid [11], but it is also possible to disconnect the converter from the rotor without disconnecting the wind turbine from the grid [14]. The generator then operates as an induction machine with a high rotor resistance. The third possibility is to keep the turbine connected to the grid and the converter connected to the rotor [9], [10], [12]. With this type of control, it is possible to resume normal operation immediately after clearance of the fault. When the dip lasts longer than a few hundred milliseconds, the wind turbine can even support the grid during the dip [9].

IV. DFIG Short-Circuit Current

This section will determine the short-circuit current supplied to the grid by a crowbar-protected DFIG. The main focus will be on the value of the first peak in the current. Generally, this will be the maximum current that is reached.

Section III gave a mathematical analysis and explanation of the fault response of an induction machine. The analysis and explanation of the voltage dip behavior of the DFIG will be given with reference to that section. The response of a DFIG is to a large extent the same as that of an induction machine. The differences will be highlighted in this section. A worst-case situation is considered in which a short circuit occurs at the stator of the machine and the turbine operates at full power.

Two important assumptions that are made during the analysis of the induction machine are not valid for a DFIG. The first is that when the bypass resistors are connected to the rotor in case of a fault, the resistance no longer can be neglected. The second is that the slip of a DFIG is not always close to zero, as is the case for an induction machine.

The maximum stator current of an induction machine in case of a short circuit at the stator terminals is given by (25). The equation was obtained in two steps. First, the term outside the rectangular brackets was determined. It represents the initial value of the current prior to the fault. In the next step, the two terms inside the brackets were determined. They represent the damping of the dc components in the stator and rotor flux, respectively.

The initial value of the current is determined under the assumption that the stator and rotor resistance can be neglected. When the bypass resistors are connected to protect the converter in case of a fault, (16) becomes

$$I_s e^{j\omega_s t} = \frac{V_s e^{j\omega_s t}}{jX_s + R_{cb}} \tag{26}$$

and the transient time constant of the rotor becomes

$$T'_r = \frac{L'_r}{R_r + R_{cb}}. \tag{27}$$

The two exponential functions inside the brackets in (25) are based on the assumption that the rotor and stator flux are 180° out of phase after half a period, implying that the current reaches its maximum value at $t = T/2$. This assumption is approximately valid for an induction machine, where the slip is small and where the stator and rotor flux are approximately in phase with each other, at the moment the fault occurs. A doubly fed induction generator can however operate at a much larger slip. This implies that at the moment of the fault, the two flux vectors are not in phase with each other.

- When the DFIG is in over-synchronous mode, the rotor flux will lead the stator flux and will take less than half a period before the two fluxes are 180° out of phase (which gives the maximum current, see Section III).
- When the DFIG is in under-synchronous mode, the opposite holds and will take more than half a period.

When the voltage at the stator terminals drops to zero, the stator and rotor flux vector stop rotating. In reality, they will rotate slowly, depending on the stator and rotor resistance. The larger the resistance, the faster they rotate. For an induction machine, this rotation could be neglected because of the small resistance. For a DFIG with bypass resistors, the rotation is no longer negligible. This is another reason why it can take less than half a period before the first peak in the current is reached.

Taking into account these differences between an induction machine and a doubly fed induction generator, (25) becomes

$$i_{s,\max} = \frac{\sqrt{2}V_s}{\sqrt{X_s'^2 + R_{cb}^2}} \left[e^{-\Delta t/T'_s} + (1-\sigma) e^{-\Delta t/T'_r} \right] \tag{28}$$

where Δt gives the time after which the current reaches its first peak. It is dependent on the slip of the machine and the value of the bypass resistors.

A larger bypass resistance will result in a smaller T'_r. At the same moment, Δt decreases. As a result, the term inside the brackets in (28) stays approximately constant. As a rough approximation, the maximum stator current is then given as

$$i_{s,\max} \approx \frac{1.8 V_s}{\sqrt{X_s'^2 + R_{cb}^2}}. \tag{29}$$

V. Value of Crowbar Resistance

From (29), it can be observed that the maximum short-circuit current of the DFIG strongly depends on the value of the crowbar resistance. This section will investigate how a good value for the bypass resistance can be determined. There are two main requirements that give an upper and a lower limit to the resistance.

1) On one hand, the resistance should be high to limit the short-circuit current.
2) On the other hand, it should be low to avoid a too high voltage in the rotor circuit.

A too high voltage can result in breakdown of the isolation material of the rotor and the converter. It is further possible that when the voltage becomes higher than the dc link voltage, large currents will flow through the antiparallel diodes of the converter, charging the dc link to an unacceptable high voltage. A lower value will result in higher currents in the rotor of the machine. The thermal time constant of the rotor will however be generally high enough to handle the short-circuit currents for a short period. Therefore, the maximum value is more important than the minimum value.

An approximation of the maximum stator current is given by (29). As all parameters are transferred to the stator side, the maximum rotor current (reduced on the stator side) will have approximately the same value. The voltage across the bypass resistors, and thus across the rotor and converter is

$$\sqrt{2}V_r \approx R_{cb} i_{r,\max}. \tag{30}$$

Combining this equation with (29), the maximum value of the bypass resistors can be determined as

$$R_{cb} < \frac{\sqrt{2}V_{r,\max} X'_s}{\sqrt{3.2V_s^2 - 2V_{r,\max}^2}} \tag{31}$$

where $V_{r,\max}$ is the maximum allowable rotor voltage. Note that it only is an approximation, as it is based on a number of assumptions and approximations.

VI. Cases

This section will present case study simulations of several wind turbines with a DFIG. A short circuit is applied to the terminals of the generator and the maximum short-circuit current supplied by the wind turbine is determined. The system has been modeled and simulated in the Simulink toolbox extension of Matlab.

The model of the doubly fed induction generator will not be described here. It can be found in [3] and [9]. 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 with the direct d-axis oriented along the stator flux position is used to control the turbine. In this way, decoupled control between the electrical torque and the rotor excitation current is obtained.

The protection system continuously measures the rotor current. When it becomes too high, the thyristors are fired and the crowbar is connected to the turbine. It is assumed to remain connected to the rotor circuit until the short circuit has cleared. The converter is deactivated during this period. The connection of the crowbar can also be followed by other actions, as has been discussed in Section IV, but the first peak in the current, which generally gives the maximum current, will be the same.

The simulation setup is shown in Fig. 4. The doubly fed induction generator is directly connected to a voltage source. In order to simulate a short circuit, the voltage drops to zero.

Simulations have been done with three doubly fed induction generators with different rated powers: 3 MW, 2.75 MW, and 660 kW. The parameters of the three generators are given in the Appendix. The crowbar resistances are chosen such that

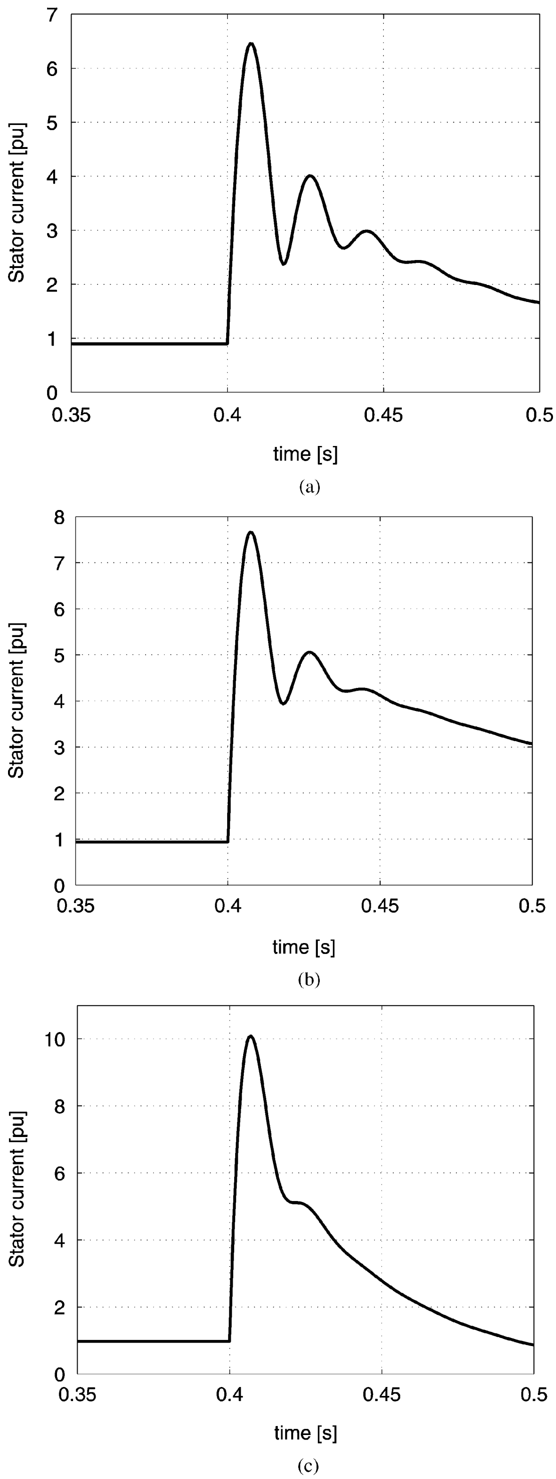

Fig. 5. Stator current of crowbar-protected doubly fed induction generator during short circuit at stator terminals. (a) 3-MW turbine. (b) 2.75-MW turbine. (c) 660-kW turbine.

the rotor voltage reaches approximately its rated value. The resulting stator currents are shown in Fig. 5.

The maximum currents calculated from (29) are 5.9 p.u., 7.8 p.u., and 11.7 p.u., respectively, and the simulated value are 6.4 p.u., 7.8 p.u., and 10.1 p.u. In the first case, the calculated value is too low, whereas in the last case it is too high. The fault between the calculated and simulated values is less than 15% in all cases. The largest fault difference is between the values for the 660-kW turbine. However, when (28) is used, a short-circuit current of 8.8 p.u. is obtained, which is too low. The difference might be caused by the fact that (28) takes the crowbar resistance into account for the damping of the rotor transients, whereas the effect is neglected in (29).

VII. Discussion

This paper investigates the short-circuit behavior of a crowbar-protected doubly fed induction generator in order to determine the short-circuit current that the generator supplies to the grid during a fault in the network. This section will give a discussion of the results.

A number of approximations and simplifications had to be made to describe the fault behavior and to determine the equations for the short-circuit current. It should therefore be noted that the equations derived in this paper only give a rough approximation. It should further be noted that a worst-case situation is considered in which the short circuit occurs on the stator terminals of the turbine. Most faults will occur further away. When, in that case, the impedance between DFIG and fault is added to the stator impedance, the same equations can however be used.

In reality, often only a few parameters of the DFIG are known. Therefore, one of the goals of this paper is to derive an equation that requires only a limited number of parameters. The parameters that are required for the equations in this paper, i.e., stator and rotor impedance will mostly be known. Only the value of crowbar resistance might be more difficult to obtain. Therefore, it is has been investigated how it can be determined on the basis of the maximum rotor voltage.

In the cases that are studied, high maximum stator currents are reached. This is because it is assumed that the rotor voltage should not exceed its maximum voltage, which requires a low crowbar resistance. Some protection schemes disconnect the converter from the rotor circuit when the crowbar is activated. In this case, higher voltages, and thus a higher resistance might be allowed that result in a lower current.

VIII. Conclusion

The short-circuit current contribution of wind turbines with doubly fed induction generators has not received much attention so far. This paper analyzed the short-circuit behavior of induction machines. Based on this analyses, approximate equations for the maximum short-circuit current have been derived. The results obtained from the approximate equations have been compared to the results of time-domain simulations. The difference between those results were shown to be less than 15%. Due to the maximum rotor voltage that is allowed, the maximum value of the crowbar impedance is small. This implies that the turbine supplies high short-circuit currents to the grid. The observed values vary from 6–10 p.u. The maximum current decreases with increasing rated power.

TABLE I
PARAMETERS OF THE 3-MW TURBINE

Parameter	Value [pu]	Parameter	Value
V_s	0.58	X_m	3.30
V_r	0.23	R_s	0.007
$X_{s\sigma}$	0.07	R_r	0.005
$X_{r\sigma}$	0.17	R_{cb}	0.04

All parameters are in p.u. with base power 3 MVA and base voltage 960 V (line–line).

TABLE II
PARAMETERS OF THE 2.75-MW TURBINE

Parameter	Value [pu]	Parameter	Value
V_s	0.58	X_m	4.20
V_r	0.20	R_s	0.0012
$X_{s\sigma}$	0.11	R_r	0.0010
$X_{r\sigma}$	0.07	R_{cb}	0.05

All parameters are in p.u. with base power 2.75 MVA, and base voltage 960 V (line–line).

TABLE III
PARAMETERS OF THE 660-KW TURBINE

Parameter	Value [pu]	Parameter	Value
V_s	0.58	X_m	2.92
V_r	0.23	R_s	0.010
$X_{s\sigma}$	0.04	R_r	0.009
$X_{r\sigma}$	0.07	R_{cb}	0.04

All parameters are in p.u. with base power 660 kVA and base voltage 690 V (line–line).

APPENDIX

This appendix gives the parameters of the three different generators that have been used (see Tables I–III).

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Johan Morren (S'03) received the M.Sc. degree in electrical engineering from the Delft University of Technology, Delt, The Netherlands, in 2000. Currently he is a Research Assistant in the Electrical Power Processing Group at the Delt University of Technology. Since 2002, he has been working towards the Ph.D. degree in power electronic aspects of grid integration of distributed generation units. His research interests include grid connection of renewable energy sources.

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

Since 1995, he has been with the Delft University of Technology, where he is currently an Associate Professor of power electronics. His research interests include electric systems for renewable energy sources and pulsed-power supplies for various applications.