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ANALYSIS AND IMPROVEMENT OF THE DOUBLY FED INDUCTION GENERATOR DURING GRID VOLTAGE FAULTS

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Abstract- The increasing size of wind farms requires power system stability analysis including dynamic models of wind Power generation. Nowadays, the most widely used generator type for units above 1MW is the doubly-fed induction machine. The behavior of these machines during grid failure is an important issue. In this paper, a theoretical analysis of the dynamic behavior of the doubly fed induction generator (DFIG) during a single phase fault is proposed. MATLAB/Simulink is implemented to build the dynamic model of DFIG. Simulation results verify that, rotor voltage and stator flux in phase which fault occurs, decrease exponentially according to the stator time constant. A detailed comparison between single-phase and three-phase voltage dip is also investigated. It is widely proved that, when fault occurs, the rotor voltage is faced with hazardous condition, so a crowbar is utilized in order to limit these adverse voltages.

Keywords: Doubly Fed Induction Generator (DFIG), Single Phase Voltage Dip, Wind Turbine.

I. INTRODUCTION

Renewable energy has been becoming a topic of great interest and investment in the world due to the concerns about emissions from fossil and depletion of fossil fuel resources [1]. Wind energy is one of the best renewable energies which is accessible to provide a sustainable supply to the world development [2]. By the end of 2003, the total installed capacity of the wind turbines has reached as much as 39.234 GW and will exceed 110 GW by the year of 2012 [3, 15]. The doubly fed induction generator (DFIG) has the largest world market share of wind turbine concept since the year 2002 because of its ability to provide variable speed operation and independent active and reactive power control in a cost-effective way [4].

Doubly Fed Induction Generators (DFIG) has become a widely used generator type in wind energy conversion. Compared to a full rated converter system, the use of DFIG in a wind turbine offers many advantages, such as: reduction of inverter cost, the potential to control torque and a slight increase in efficiency of wind energy extraction [5]. Since the stator of the DFIG is directly connected to the grid, and the capacity of the excitation converter is limited, the converter is quite sensitive to the grid disturbances. Recent wind turbines have to provide the capability of riding through this voltage dips [6].

When severe grid voltage dips occurs, the power generated by the DFIG cannot be transmitted to the grid in time, causing large fault currents in the stator. Because of the magnetic coupling between stator and rotor, the stator fault currents are further transmitted into the rotor causing uncontrollable excessive rotor over-currents, which will damage the power electronic devices of the converter. Also, the electromagnetic torque of the DFIG starts to oscillate with big amplitude, causing great stress concussion to the mechanical system of wind turbine [7]. In these disruptive situations, a crowbar which is a device that connects the rotor windings of a DFIG together is used [13].

This paper provides a study of the dynamics of the grid connected wind turbine with DFIG in a single line voltage fault. It is observed that, the voltage dip causes the strong over voltage in the rotor and if the rotor converter cannot handle this overvoltage, over-currents in the stator and the rotor of the DFIG will be created.

This paper is organized as follows. In section II, the basic model of DFIG is proposed, then the analysis under a single-phase fault on phase B of DFIG is described and at the end, the behavior of the DFIG in 60% voltage dip in phase B is explained. Proposed DFIG is simulated with MATLAB\Simulink in section III. Comparison between stator fluxes and rotor voltages in single-phase and three-phase voltage dip is organized in section IV. Implementation of the crowbar for developing the fault conditions is included in section V. Conclusions is also summarized in section VI.

II. DYNAMIC ANALYSIS DURING A SINGLE-LINE FAULT

A. Model Description

Figure 1 is a basic configuration of a wind turbine based on a DFIG. The stator is directly connected to the grid while the rotor is interfaced through a back-to-back power converter. In contrast to a Singly-Fed Induction Generator, DFIG is independent from the speed.

Therefore, it is possible to realize a variable speed wind generator allowing adjusting the mechanical speed to the wind speed and hence operating the turbine at the aerodynamically optimal point for a certain wind speed range.

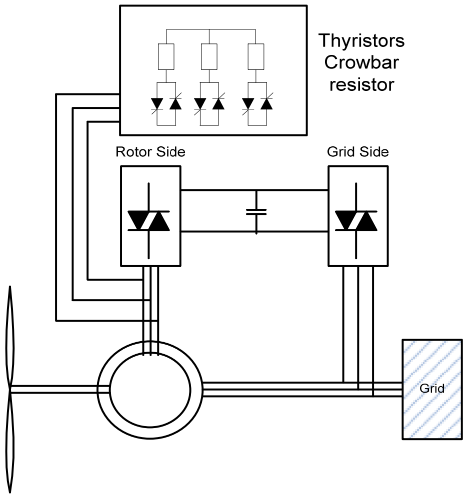

Figure 1. Doubly-fed induction generator system

B. Control Method of DFIG

Controlling of the DFIG has two main goals. The first one is to accomplish maximum wind power capture, in this method control of active power and DFIG speed is the target. The second one is the control of the stator’s output reactive power [10]. The active and reactive powers of the DFIG are mainly proportional to the rotor current, so with controlling the rotor current, we achieve appropriate active and reactive power. Rotor-side converter is able to control the rotor current.

The control method of the rotor-side converter is divided into two links, one is speed control and the other is current control [11]. Figure 2 shows the control system of the rotor side converter.

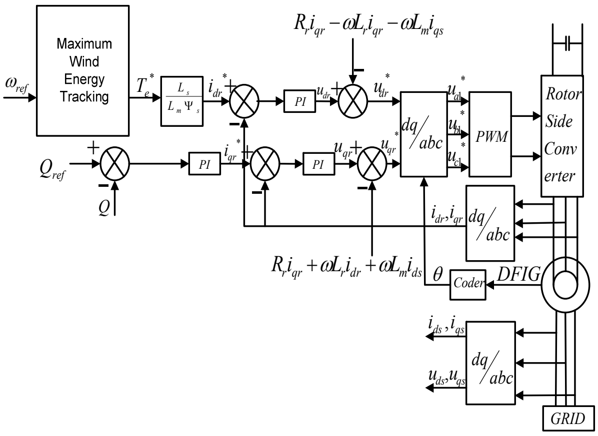

Figure 2. Control system of the rotor side converter

The main purpose of the grid-side converter is to fix the DC bus voltage, to maintain the input current sinusoidal and to control the input power factor. If there is a balance in active power between AC and DC side, DC bus voltage will be stable. Therefore, with active power control of the AC-side, we can maintain the DC bus voltage fixed. As the AC-side voltage is constant, we can control the input active power in the DC-side to fix the DC bus voltage. The input power factor control is actually identical with the control of the input current with reactive power component. So, the grid converter control system is divided into two sections: one is speed control and the other is the current control [11]. Figure 3 shows this control system.

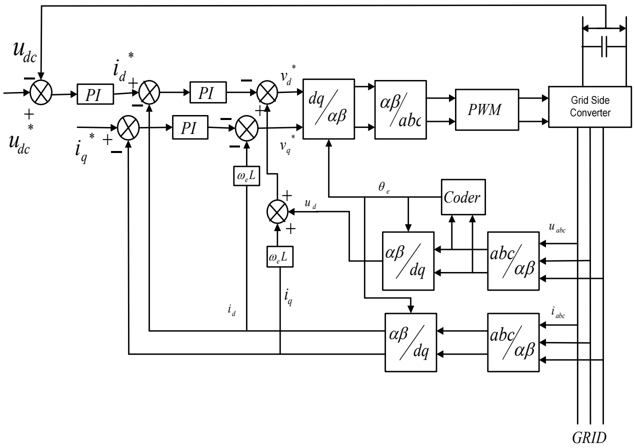

Figure 3. Control system of the grid side converter

C. Generator Model

The Park model is commonly used for induction generator [8, 14]. The generator is basically a slip-ring induction machine which can be modeled according to [9] in the following equations:

$$\vec{v_s}=R_s.\vec{i_s}+\frac{d}{dt}\vec{\varphi_s} \quad (1)$$

$$\vec{v_r}=R_r.\vec{i_r}+\frac{d}{dt}\vec{\varphi_r}-j\omega\vec{\varphi_r} \quad (2)$$

In the DFIG, $\vec{v_s}$ is directly imposed by the grid voltage and is constant due to the fix grid voltage, but $\vec{v_r}$ is controlled by the converter and has an important role in controlling the machine. The stator and rotor fluxes are given by [9]:

$$\vec{\varphi_s}=l_s.\vec{i_s}+l_m.\vec{i_r} \quad (3)$$

$$\vec{\varphi_r}=l_r.\vec{i_r}+l_m.\vec{i_s} \quad (4)$$

$\vec{v_r}$ is induced by the variation of the rotor flux, which can be calculated from Equations (3) and (4):

$$\vec{v_r}=\frac{l_m}{l_s}(\frac{d}{dt}-j\omega).\vec{\varphi_s}+(R_r+\sigma.l_r(\frac{d}{dt}-j\omega)).\vec{i_r} \quad (5)$$

In the DFIG, R_r and $\sigma.l_r$ are small and we can neglect them in Equation (5), therefore:

$$\vec{v_r}=\frac{l_m}{l_s}(\frac{d}{dt}-j\omega).\vec{\varphi_s} \quad (6)$$

Before the fault, the stator voltages which directly come from grid are sinusoidal wave forms with constant amplitude (V_s):

$$v_{sa}(t)=V_s\sin(\omega_s t)$$
$$v_{sb}(t)=V_s\sin(\omega_s t-120) \quad (7)$$
$$v_{sc}(t)=V_s\sin(\omega_s t+120)$$

By neglecting the stator resistance in (1), the stator fluxes are given by:

$$\varphi_{sa}(t)=\frac{V_s}{\omega_s}\sin(\omega_s t\text{-}90)$$
$$\varphi_{sb}(t)=\frac{V_s}{\omega_s}\sin(\omega_s t\text{-}210) \quad (8)$$
$$\varphi_{sc}(t)=\frac{V_s}{\omega_s}\sin(\omega_s t+30)$$

By substituting (8) in (6) the rotor voltages are given by:

$$v_{ra}(t)=\frac{l_m}{l_s}V_s s.\sin(\omega_s t\text{-}90)$$
$$v_{rb}(t)=\frac{l_m}{l_s}V_s s.\sin(\omega_s t\text{-}210) \quad (9)$$
$$v_{rc}(t)=\frac{l_m}{l_s}V_s s.\sin(\omega_s t+30)$$

where, s is slip of the rotor ($s=\frac{\omega_s-\omega}{\omega_s}$). In (9), it is observed that, the rotor voltage is directly proportional to slip, and in a constant slip, the rotor voltage is a sinusoidal wave form with amplitude of $\frac{l_m}{l_s}V_s s$.

Now it is assumed that, the DFIG is in normal operation until time t_0=0 and then a single phase fault is happened in phase B of the DFIG. The analysis of operation under a fault is given in the next part.

D. Analysis under a Single Phase Fault on Phase B

When a single phase fault occurs on phase B, its voltage becomes zero suddenly, but the other phase's voltage are the same in the (7).

$$v_{sb}(t\geq t_0)=0 \quad (10)$$

For simplicity it is assumed that the rotor is open circuited ($i_r(t)$=0). From (3), (4) and (1):

$$\vec{v_s}=\frac{R_s}{l_s}.\vec{\varphi}_s+\frac{d}{dt}\vec{\varphi} \quad (11)$$

with (10) and (11):

$$\varphi_{sb}(t\geq t_0)=\frac{V_s}{\omega_s}\sin(\omega_s t\text{-}210)\exp(\text{-}t\frac{R_s}{l_s}) \quad (12)$$

and the two other phase's fluxes are the same as (8). It is observed in (12) that the stator flux in the phase which fault occurs is decreasing with time constant of $\frac{R_s}{l_s}$ but the fluxes of phase A and C are the same sinusoidal before the time t_0.

By substituting (12) in (6) and neglecting the term $\frac{R_s}{l_s}$ due to its low value, the rotor voltage in phase B is given by (13) and the other two phases are the same as (9):

$$v_{rb}(t\geq t_0)=\frac{l_m}{l_s}.V_s(1\text{-}s).\sin(\omega_s t\text{-}120) \quad (13)$$

The Equation (13) shows that when a fault occurs in phase B, the rotor voltage in phase B which was directly proportional to slip (s) before fault, now is directly proportional to (1-s), and the two other phases are proportional to (s) after and before the fault.

E. Analysis under 60% Voltage Dip on Phase B

When a 60% voltage dip occurs to phase B, its voltage's amplitude is changed from $V_1=V_s$ to $V_2=0.4\,V_s$, so:

$$v_{sb}(t>t_0)=0.4V_s \quad (14)$$

By substituting (14) to (11) the stator flux is obtained:

$$\varphi_{sb}(t\geq t_0)=\frac{V_2}{\omega_s}\sin(\omega_s t\text{-}210)+\frac{V_1\text{-}V_2}{\omega_s}\exp(\text{-}t\frac{R_s}{l_s}\text{-}\frac{\pi}{2}) \quad (15)$$

Equation (15) shows that the stator flux in phase B consists of a rotational term that is determined by the grid voltage, and a term with a constant argument due to the natural mode. In this situation, the two other phase's fluxesare the same as they were before t_0=0. By substituting (15) in (6), the rotor voltage is given by:

$$v_{rb}(t\geq t_0)=\frac{l_m}{l_s}(sV_2e^{j\omega_r t}\text{-}(1\text{-}s)(V_1\text{-}V_2)e^{j\omega t}e^{\text{-}t\frac{R_s}{l_s}} \quad (16)$$

and the two other phase's rotor voltages are the same as (9). As it is observed in equation (10) to (16), in a full dip fault, the rotor voltage is proportional to (1-s), while before the fault it was proportional to (s). In a partial voltage dip, the rotor voltage has two terms, the first one is caused by V_2, is proportional to (s) and the second one is caused by the natural flux and is proportional to (1-s) (V_1-V_2). In a three phase fault, equation (16) is applied to all three phases with 120 degree phase shifted wave form.

III. SIMULATION RESULTS

This proposed DFIG is simulated to demonstrate the features and theoretical analysis. A 3 KW DFIG is simulated using MATLAB/Simulink. The parameters which have been used for simulations are given in Table 1. A single phase fault occurs in time t_0=0 and continues for 0.4 sec. For simplicity the transient time after the fault in 0.4 sec is neglected. For better view, in all of the figures, only phase A and phase B have been shown. Phase C obtains from phase A that is shifted by 120 degree.

Table 1. Simulation parameters

Rated power	3KW
Rated stator voltage	U_n=380 v
Rated frequency	50 Hz
Stator resistance	R_s=1.2 Ω
Mutual inductance	l_m=0.127 H
Stator leakage inductance	l_{Ls}=0.0022 H
Number of pole pairs	P_n=2
Fault time	T_0=0

Figure 4 shows the wave forms of the stator fluxes of the DFIG (pu) when a single phase fault occurs in phase B, which obtained from Equations (8) and (12). When a fault is occurred in t_0=0 in phase B, it's flux wave form begins to decrease toward zero with time constant (blue wave form) until removing the fault, but the two other phase's fluxes are sinusoidal because there are no faults on phases A (red wave form) and C. Figure 5 shows the wave forms of the rotor voltages of the DFIG when a single phase fault occurs in phase B.

It is observed that, before time t_0=0, the rotor voltages are sinusoidal wave forms, but after t_0=0 the rotor voltage in phase B (blue wave form) decreases exponentially until about 0.35sec when it becomes around zero and the two other phase's voltages are sinusoidal like before. These results obtained from Equations (9) for phase A and C and (13) for phase B. Figure 6 shows the wave forms of the stator flux of the DFIG (pu), when the voltage amplitude of the phase B decreases to $0.4V_s$ or in other words a 60% voltage dip occurs in phase B.

It is observed in Figure 6 that after 0.35sec and before the elimination of the fault, the stator flux in phase B is a sinusoidal wave form with amplitude of $\frac{0.4V_s}{\omega_s}$ which is shown with blue waveform and 0.35 sec is the time that stator flux decreases exponentially to reach its final value ($0.4V_s$), because the stator flux in phase B is not able to reach its final value instantly. Figure 7 shows the wave forms of the rotor voltages of the DFIG when a 60% voltage dip occurs in phase B.

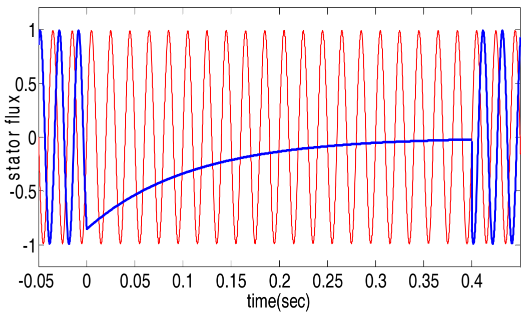

Figure 4. Stator fluxes in single phase fault

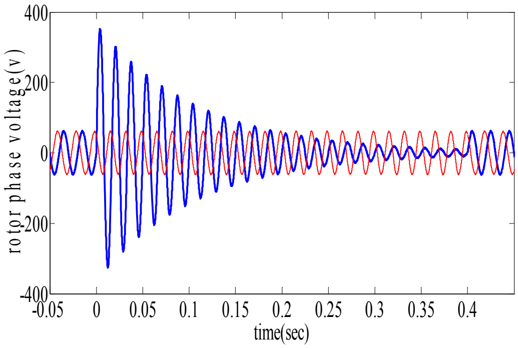

Figure 5. Rotor voltages in a single phase fault

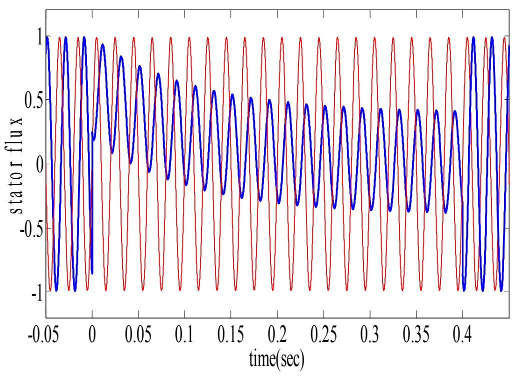

Figure 6. Stator fluxes in single phase 60% voltage dip

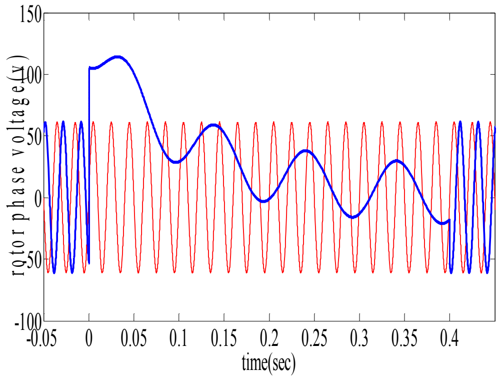

Figure 7. Rotor voltages in a 60% voltage dip in phase B

It is observed in (16) the rotor voltage after fault has two terms. The first one is created by grid voltage after the fault (V_2) and its amplitude is small as it is proportional to the slip and its frequency is ω_r=ω_s-ω. The second voltage is a transient term and its amplitude can be important because it is proportional to the depth of the fault voltage (V_1-V_2). In addition, its frequency is the rotor electrical speed ω. In Figure 7, the rotor voltage after 0.3 sec has a sinusoidal wave form with slip frequency ω_r. In the next part a comparison between a single-phase and a three-phase fault is investigated.

IV. COMPARISON BETWEEN A THREE-PHASE AND A SINGLE-PHASE VOLTAGE DIP

In a three-phase fault we consider a condition in which the stator voltages decrease to $0.4V_s$ or a 60% voltage dip occurs in all the phases. Just like a single-phase fault, in a three-phase fault when a stator voltage in one phase decreases immediately, its flux cannot decrease instantly. The stator flux decreases exponentially to its final value. We have the same conclusion for the rotor voltages in a three-phase voltage dip, which the rotor voltages in phases A, B and C have two terms, first one has small amplitude and its frequency is ω_r but the second one has remarkable amplitude and its frequency is ω. Figure 8 shows the wave forms of the rotor voltages in a 60% three-phase voltage dip which are given by Equation (16) and for the other two phases are phase shifted by 120 degree.

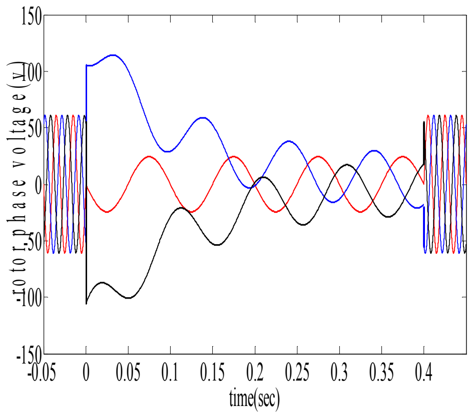

Figure 8. Rotor voltages in a 60%three phase voltage dip

It is observed that in three phase voltage dip, all the phases have two terms and after 0.35 sec all the phases have a sinusoidal wave form with slip frequency of ω_r, but in the single-phase fault just one phase have this condition. Figure 9 shows the stator fluxes of DFIG (pu) when a 60% three-phase voltage dip occurs, which are given by Equation (15) that for other two phases is shifted by 120 degree. In this figure only phase B has been shown.

V. IMPLEMENTATION OF THE CROWBAR

The duty of the crowbar system is to protect the rotor side converter and rotor windings against over voltages and over currents. It is usually includes three phase rectifier, power resistance and series switches. These series switches can be anti-parallel Thyristor, GTO or IGBT that are used for controlling the crowbar system. Conventionally, the crowbar is applied for an extended duration to fully demagnetize the rotor [12]. A crowbar activation period typically lasts about 120 ms. but, this can lead to a 100 ms post fault period of at least 50% reactive power absorption and relevant voltage dip. A new design of crowbar has been presented in [13]. Figure 10 shows the crowbar circuit which consists of a three-phase rectifier, power resistor, and series IGBT switch. The quick turn-off ability of an IGBT has led to decrease the activation period of a crowbar to 10-20 ms [13].

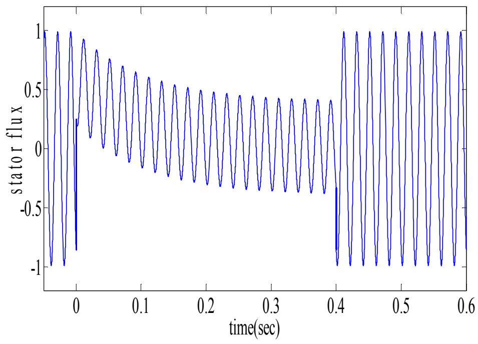

Figure 9. The stator fluxes in a 60% three-phase voltage dip

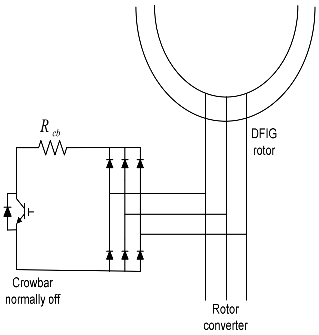

Figure 10. The crowbar circuit

Because the rotor voltage in Figure 5 after the fault has pick value near 400V, it will lead to over-currents in the rotor and the stator, so the crowbar will be activated and the rotor voltages will become zero after the activation time of the crowbar (10 ms). Figure 11 shows the crowbar operation in single-phase voltage fault on the stator of the DFIG. In Figure 11, only phase A (red wave form) and phase B (blue wave form) have shown.

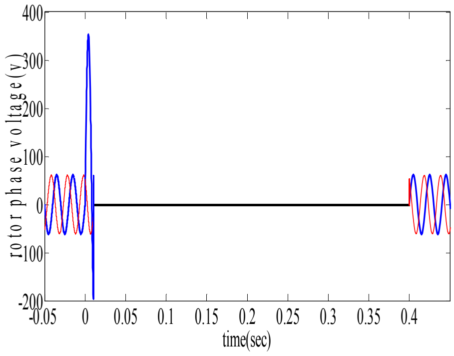

Figure 11. The crowbar operation after fault in single-phase voltage fault on the stator

It is observed from simulations that, because of the voltage dip, when a voltage in the rotor of the DFIG begins to rise up quickly, the crowbar acts and the rotor voltages become zero until the fault is cleared.

VI. CONCLUSIONS

This paper presents an analysis of the DFIG during a single-phase voltage dips. For this, dynamic modeling of the DFIG is proposed. When voltage dips occur, there is a disturbance in power transmission between DFIG and grid, which will cause large fault currents in the stator. Because of the magnetic coupling between the stator and rotor, the stator fault currents are transmitted into the rotor, and this condition causes uncontrollable rotor over currents. So it will damage the converter of the DFIG and create oscillations of the electromagnetic torque of the DFIG with big amplitude.

A crowbar which connects the rotor windings of a DFIG together, results zero voltage of the rotor phases and decreases the probability of converter damage. Also, the rotor and the stator over-currents are reduced. Hence, studying the behavior of the DFIG in fault condition is the best way to solve these problems.

NOMENCLATURES

l_m: Magnetizing inductance
l_{ls}, l_{lr}: Stator and rotor leakage inductances
l_s, l_r: Stator and rotor self-inductances
R_s, R_r: Stator and rotor resistances
$\vec{v}_s$, $\vec{v}_r$:Stator and rotor voltage space vectors
$\vec{\varphi}_s$, $\vec{\varphi}_r$: Stator and rotor voltage space vectors
ω_s, ω_r, ω: Synchronous, slip and rotor angular frequencies

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BIOGRAPHIES

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