CONTROL STRATEGY FOR THE ROTOR SIDE CONVERTER OF A DFIG-WT UNDER BALANCED VOLTAGE SAG

Kleber Lima
Federal University of Ceara
klima@dee.ufc.br

Álvaro Luna
Technical University of Catalonia
luna@ee.upc.edu

Edson H. Watanabe
Federal University of Rio de Janeiro
watanabe@coe.ufrj.br

Pedro Rodríguez
Technical University of Catalonia
prodriguez@ee.upc.edu

***Abstract* – This paper proposes a new control technique to improve the fault-ride through capability of doubly fed induction generators (DFIG). In such generators the appearance of severe voltage sags at the coupling point make rise to high over currents at the rotor/stator windings, something that makes necessary to protect the machine as well as the rotor side power converter. As a difference with the most extended solution, that reduces these currents by means of the connection of a crowbar circuit, this works intends to enhance the DFIGs response in such conditions without introducing extra hardware in the system. To this end, the proposed control system feedback the stator currents as the rotor current reference during the fault, until they are driven to their nominal values. The feasibility of this proposal has been proven by means of mathematical and simulation models, based on PSCAD/EMTDC, as well as experimental results from a prototype of 6kW rated power.**

***Keywords* – Wind generation, Direct Power Control, Field-oriented control, ride-through capability.**

I. INTRODUCTION

The increasing capacity of the installed wind power generation facilities, as well as the high scale penetration of such systems in the next future, is a new challenge for the transmission system operators (TSO). This new scenario have made necessary to renew the existing grid codes (GC), that now include specific requirements regarding the operation of wind power generators and farms. Among these new requirements, those that concern the capability of wind power generators to remain connected to the grid, in case of grid voltage sags, have gained a great importance.

This feature, known as fault ride-through (FRT) capability, states the fault condition boundaries among the ones a wind turbine (WT) should not get disconnected from the grid and in some cases, as in the Spanish and German GC, give also the operation pattern for the system under such conditions.

At the present time WTs based on DFIG (DFIG-WT), controlled by means of back to back converters, constitute the 50% of the installed WTs worldwide. In such systems fulfilling the new FRT requirements is not a simple job, as due to its connection topology, they are specially sensitive to any voltage sag.

In a DFIG when the voltage at the stator windings drops a sudden overcurrent appears in the stator that in turn, is induced to the rotor windings. This current peak is able to damage the machine and the rotor side converter, and as a consequence, the system must get protected.

Within this field several studies focused on improving the FRT capability of DFIG-WTs have been presented in [1]-[13]. Among the proposed solutions, those based on limiting the overcurrents in the rotor converter by means of connecting crowbar circuits during the fault have been broadly used [14]-[16]. In Fig. 1 the block diagram of a DFIG WT equipped with such circuit is shown.

However, this kind of solution implies the installation of extra hardware in the system, something that finally increases the costs and hinders its reliability, as the control system should became more complex. Moreover, and despite the fact that a crowbar is able to reduce the current peaks under sag conditions, this device does not avoid the disconnection of the rotor side converter after the fault is detected.

In addition, the design of such protection is calculated considering the present features of the wind power system so any future change of its configuration would affect its performance.

Other alternatives to crowbars, as the inclusion of static keys between the stator and the electrical grid, presented by Petterson [17], or the stator flux damping proposed by Næss [18] have been also published. However all these techniques require also the installation of extra active/passive elements in the power system.

The aim of this paper is to propose a new control technique for the rotor side converter that would permit to guarantee the controlability of DFIG WTs during severe voltage sags without adding extra hardware.

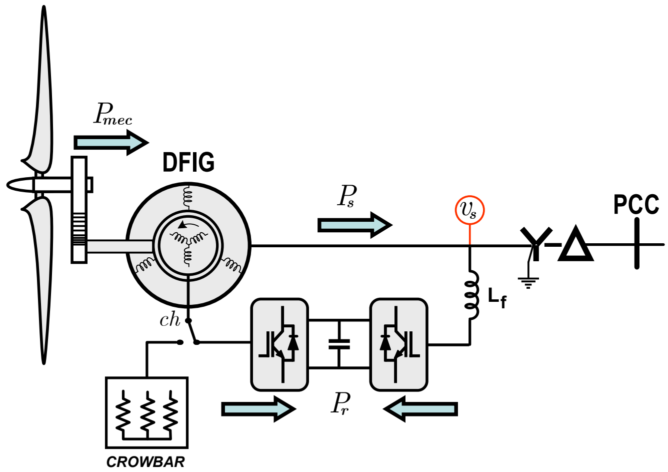

Fig. 1. Operation of a grid connected DFIG-WT controlled by means of a back to back power converter.

II. MODELING OF THE GENERATOR

This section will be devoted to the modeling of the DFIG. The objective of this part will be focused on finding a simple relationship between the state space variables that could permit to predict the behavior of DFIG under fault conditions. Later this analysis will constitute the basis for the design of the control system for the rotor side converter.

A. Reference Frame System

In this paper the rotor side controller has been implemented considering a field oriented control (FOC) philosophy in the dq reference frame [19]. In this kind of systems the dq axis are aligned with the stator flux, as it can be noticed from Fig. 2. This reference frame, known as synchronous reference frame (SRF), is useful in order to reduce partially the complexity of the mathematical equations that describe the system.

As it can be deducted from Fig. 2, and due to the low leakage stator inductance, the stator voltage v_s can be considered to be 90º leaded with respect the statoric flux, and hence almost completely aligned with the in-quadrature axis, q, while the magnetizing current in the stator haves a single component in the d-axis.

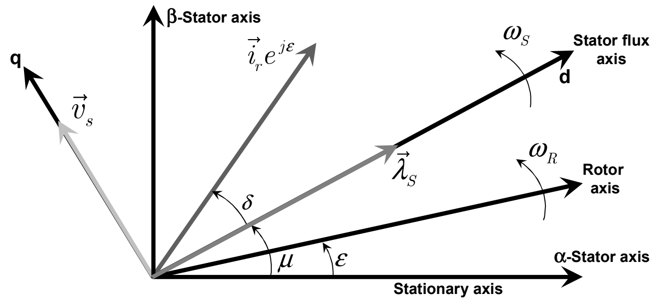

Fig. 2. Vectorial diagram in the dq reference frame considering a field oriented control philosophy.

B. Voltage and Magnetic Flux Equations

The voltage and magnetic flux of the stator in a fifth order model can be written as:

$$\begin{aligned} v_{sd} &= R_s i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_s \lambda_{sq}, \\ v_{sq} &= R_s i_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_s \lambda_{sd}, \\ \lambda_{sd} &= L_s i_{sd} + L_m i_{rd}, \\ \lambda_{sq} &= L_s i_{sq} + L_m i_{rq}. \end{aligned} \tag{1}$$

In an analogous way the equations that describe the dynamics of the voltage and magnetic flux at the rotor are:

$$\begin{aligned} v_{rd} &= R_r i_{rd} + \frac{d\lambda_{rd}}{dt} - \omega_{slip} \lambda_{rq}, \\ v_{rq} &= R_r i_{rq} + \frac{d\lambda_{rq}}{dt} + \omega_{slip} \lambda_{rd}, \\ \lambda_{rd} &= L_r i_{rd} + L_m i_{sd}, \\ \lambda_{rq} &= L_r i_{rq} + L_m i_{sq}. \end{aligned} \tag{2}$$

Where λ_s is the stator flux and λ_r is the rotor flux; L_s, L_r and L_m are the stator, rotor and magnetizing inductances, respectively; v_s and i_s are the stator voltages and currents; v_r and i_r are the rotor voltages and currents; R_r and R_s are the rotor and stator resistances; ω_r and ω_s are the synchronous and rotating angular frequencies, respectively, ω_{slip} is the slip frequency.

Considering that the system described by (1) and (2) is linear, something that assumes that the magnetic circuit of the DFIG is linear, and later applying the Laplace transformation it is possible to obtain the following statoric currents in the synchronous reference frame [20]:

$$\begin{aligned} i_{sd} = &\frac{(L_s s + R_s) v_{sd} + \omega_s L_s v_{sq}}{(L_s^2 s^2 + 2 L_s R_s s + R_s^2 + \omega_s^2 L_s^2)} \\ &- \frac{(L_s s^2 + R_s s + \omega_s^2 L_s) L_m i_{rd} - R_s \omega_s L_m i_{rq}}{(L_s^2 s^2 + 2 L_s R_s s + R_s^2 + \omega_s^2 L_s^2)}, \end{aligned} \tag{3}$$

$$\begin{aligned} i_{sq} = &\frac{-\omega_s L_s v_{sd} + (L_s s + R_s) v_{sq}}{(L_s^2 s^2 + 2 L_s R_s s + R_s^2 + \omega_s^2 L_s^2)} \\ &- \frac{R_s \omega_s L_m i_{rd} + (L_s s^2 + R_s s + \omega_s^2 L_s) L_m i_{rq}}{(L_s^2 s^2 + 2 L_s R_s s + R_s^2 + \omega_s^2 L_s^2)}. \end{aligned} \tag{4}$$

The equations (3) and (4) can be simplified considering that in a field oriented control system the stator flux is aligned with the dq reference frame, and hence its quadrature component is null. Besides, and assuming that the leakage inductance value is low, the stator voltage vector can be considered to be almost aligned with the in-quadrature axis. In this manner the previous equations can be rewritten as:

$$i_{sd} = \frac{1}{L_s} \frac{\omega_s}{s^2 + 2(R_s/L_s)s + \omega_s^2} v_{sq} - \frac{L_m}{L_s} i_{rd}, \tag{5}$$

$$i_{sq} = \frac{1}{L_s} \frac{s + R_s/L_s}{s^2 + 2(R_s/L_s)s + \omega_s^2} v_{sq} - \frac{L_m}{L_s} i_{rq}. \tag{6}$$

The equations (5) and (6) show how any variation in the stator voltage introduce oscillations in the dq components of the stator currents in the synchronous reference frame. The frequency of such oscillation is equal to the grid frequency and its damping is very poor, due to the low value of the statoric resistance, R_s (generally around 0.005 p.u)

This phenomenon can be specially noticed during a voltage sag. If the voltage sag is balanced the stator currents in dq oscillate at ω_s. However, if the sag is unbalanced the negative sequence components that appear forces oscillations equal to $2\omega_s$ in v_{sd} and v_{sq} that shall be added to the ω_s ones that are generated by the positive sequence sudden change.

In the steady state the voltage in the stator windings, (7) and (8), can be written as:

$$i_{sd} = \frac{1}{L_s \omega_s} v_{sq} - \frac{L_m}{L_s} i_{rd}, \tag{7}$$

$$i_{sq} = \frac{R_s}{L_s^2 \omega_s^2} v_{sq} - \frac{L_m}{L_s} i_{rq} \cdot \quad (8)$$

Analyzing (8), it can be concluded that the multiplicative factor of the in-quadrature component of the stator's voltage tends to zero. Thus, and considering that $R_s \ll L_s^2 \omega_s^2$, this equation can be reduced to:

$$i_{sq} = -\frac{L_m}{L_s} i_{rq} \cdot \quad (9)$$

In equation (9), i_{sq}, reveals the linear dependence between the stator and rotor current components on the in-quadrature axis.

On the other hand, the final value of i_{ds} in (7) depends upon two terms. The first one, considering the steady state conditions, describes its relationship with the magnetization's current, while the second depends on the rotor's direct current component.

C. Reliability of the Presented Model

In this section, the DFIG model presented in (5), (6), (7) and (9) is validated through simulations carried out in PSCAD/EMTDC. The simulation results, depicted in Fig. 3 and Fig. 4, show the response of the stator and rotor currents in the *dq* axes when a balanced voltage sag at the PCC occurs at *t = 2* s and last after 200 ms. The first graph is devoted to the stator currents performance, while the second one is focused on the behavior of the rotor current. In the figures the output of a classical fifth order model is also shown, in order to prove the accuracy of the proposed model.

As it can be noticed in both cases these results permit to conclude that the proposed simplified model describes the DFIG's behavior with a reasonable degree of accuracy.

The plots in Fig. 3 and Fig. 4 show the current peaks that appear in the rotor and in the stator windings, when the fault occurs, as well as when it is cleared. Although its magnitude depends upon other parameters, the simulations show peaks that exceed two times the rated current of the rotor side converter, something that would damage seriously this device in a real facility.

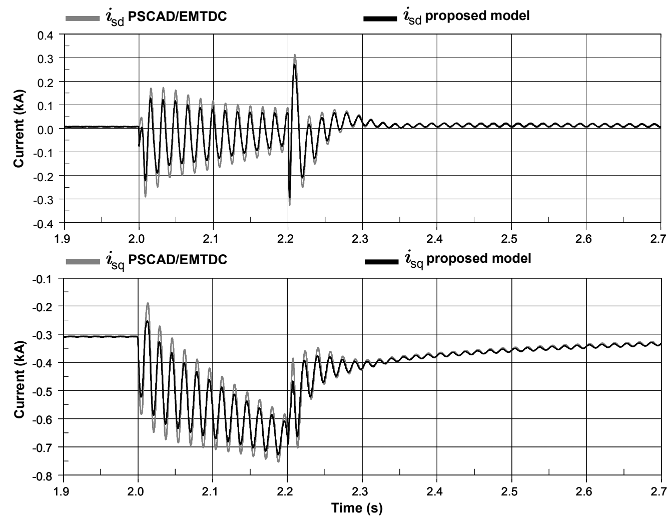

Fig. 3. Transient response of the stator current with the proposed simplified model in front of the traditional fifth order model, when a three phase balanced fault is applied at t = 2.0 s and cleared after 200ms.

III. CONTROL STRATEGIES FOR A DFIG-WT UNDER FAULT CONDITIONS

This proposal intends also to design a control strategy for reducing the currents in the stator/rotor windings when a fault affects the generator. The philosophy of this control is to feedback the measured stator currents as the set point for the current controller of the rotor side converter when a voltage dip occurs. In this manner the current control system synthesizes rotor currents that generate currents waveforms in the stator windings, with the same shape of the currents generated during the sag but in counter-phase.

The objective of this strategy is to reduce the stator over-currents, and, as a consequence, the rotor over-currents that appear in the DFIG windings during the sag, by means of adapting the control of the rotor side converter during this kind of events and without using any external crowbar circuit.

The dashed line of the control diagram of the rotor converter, in Fig. 5, is responsible of controlling the DFIG during the voltage sag, when the switch will be placed in position 2. When this switch is triggered the external *PQ* control loop gets disconnected, and the rotor currents set point matches the measured values of the stator currents in the *dq* reference frame, as it is indicated in (10) and (11)

$$i_{rd}^* = i_{sd} \quad (10)$$

$$i_{rq}^* = i_{sq} \quad (11)$$

Assuming that the current control of the converter is fast and accurate, so that the currents of the rotor track the references given in (10) and (11), then (5) and (6) results in (12) and (13):

$$i_{sd} = i_{rd} = \frac{1}{L_s + L_m} \frac{\omega_s}{s^2 + 2\left(R_s / L_s\right) s + \omega_s^2} v_{sq}, \quad (12)$$

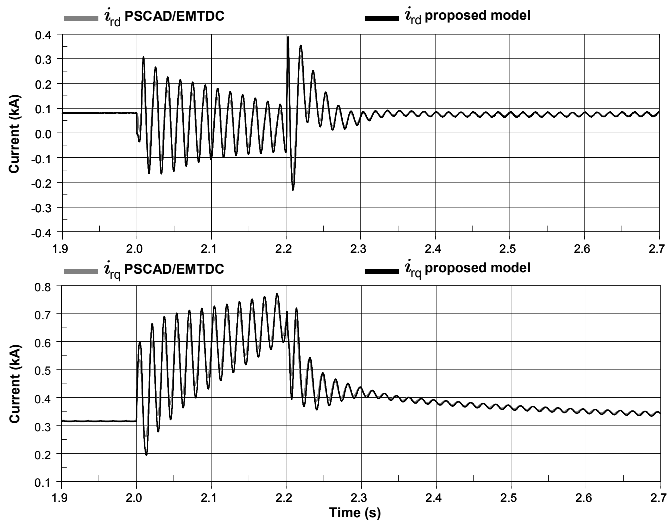

Fig. 4. Transient response of the rotor current with the proposed simplified model in front of the traditional fifth order model, when a three phase balanced fault is applied at t = 2.0 s and cleared after 200ms.

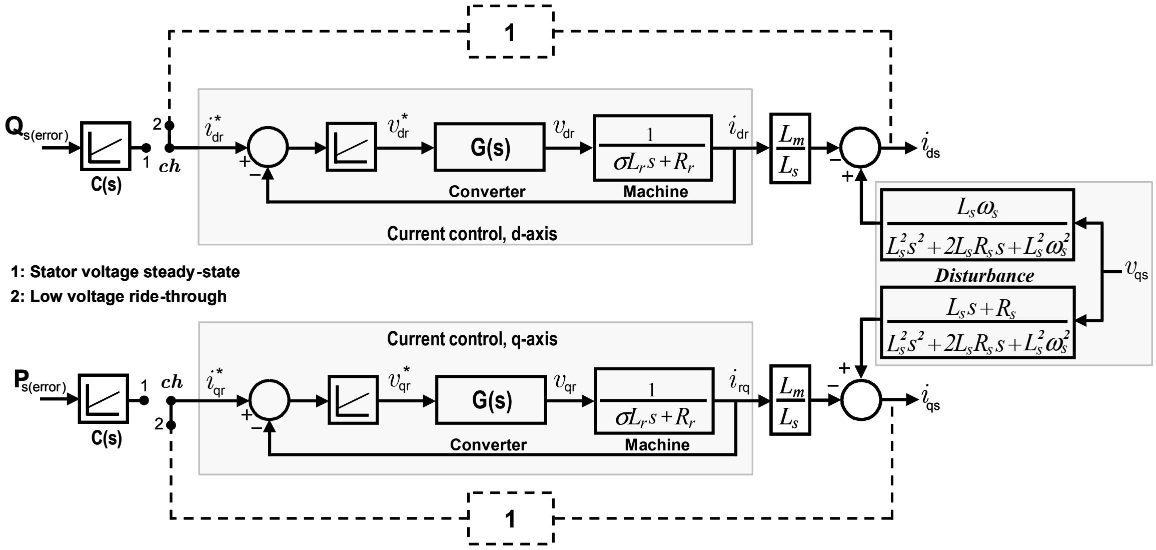

Fig. 5. Layout of the proposed control system for the rotor side converter. The position of the switch is modified from '1' to '2' when the fault is detected, enabling the proposed control strategy during the sag.

$$i_{sq} = i_{rq} = \frac{1}{L_s + L_m} \frac{s + R_s/L_s}{s^2 + 2\left(R_s/L_s\right)s + \omega_s^2} v_{sq} \cdot \qquad (13)$$

IV. SIMULATION AND EXPERIMENTAL RESULTS

The performances of the discussed strategies have been tested considering a three phase balanced voltage sag, produced by a three phase short circuit in the distribution grid. The voltage waveforms during the sag are depicted in Fig. 8.

The performance of the rotor and stator currents when both strategies are implemented can be compared thanks to the simulation plots depicted in Fig. 9 and Fig. 10. The first plot shows the response of the rotor currents during the sag, while the second one in focused on the stator current behavior.

As it can be noticed in Figures 9, 10 and 12, strategies permit to reduce the currents in the generator's windings during the fault. However the proposed algorithm produces minor oscillations in the current waveforms if compared with the simulation response obtained with the zero power set point strategy.

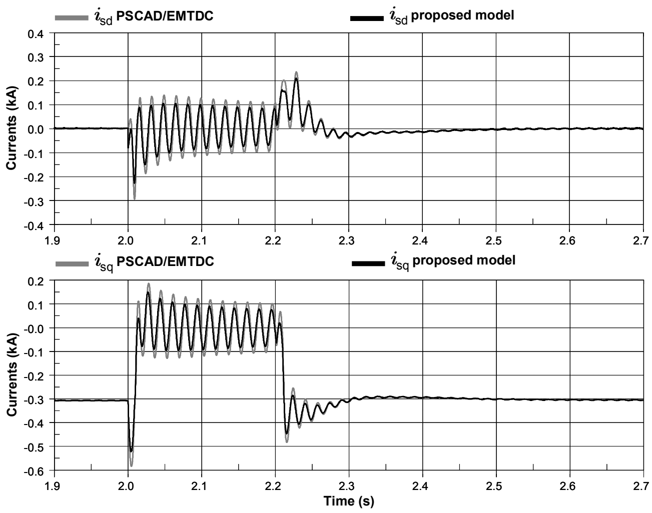

Fig. 6. Transient response of the stator current *using the proposal strategy* with the proposed simplified model in front of the traditional fifth order model, when a three phase balanced fault is applied at t = 2.0 s and cleared after 200ms.

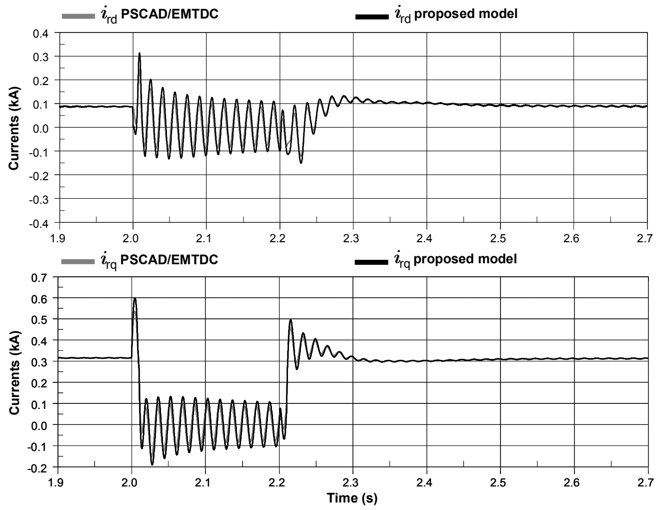

Fig. 7. Transient response of the rotor current *using the proposal strategy* with the proposed simplified model in front of the traditional fifth order model, when a three phase balanced fault is applied at *t = 2.0* s and cleared after 200ms.

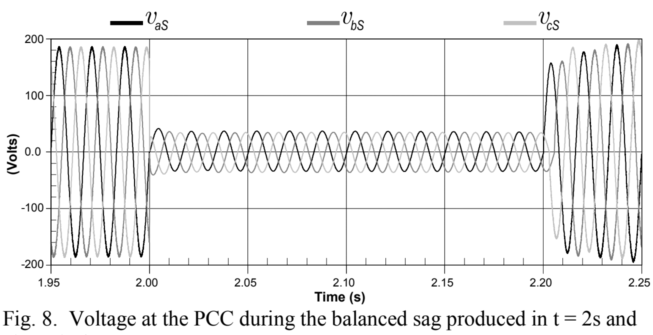

Fig. 8. Voltage at the PCC during the balanced sag produced in t = 2s and cleared after 200 ms.

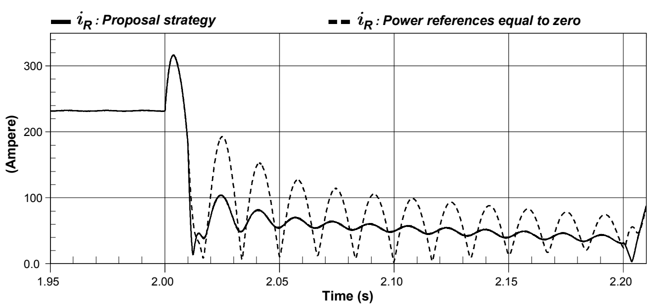

Fig. 9. Rotor currents performance under balanced sag conditions.

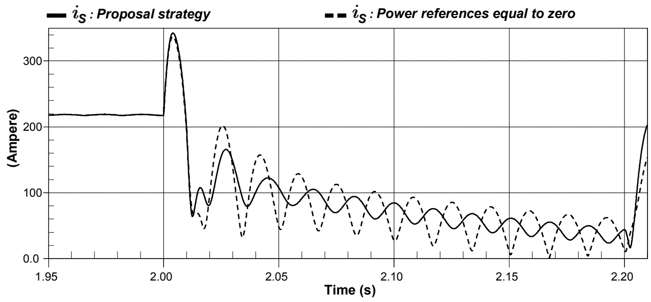

Fig. 10. Stator currents performance under balanced sag conditions.

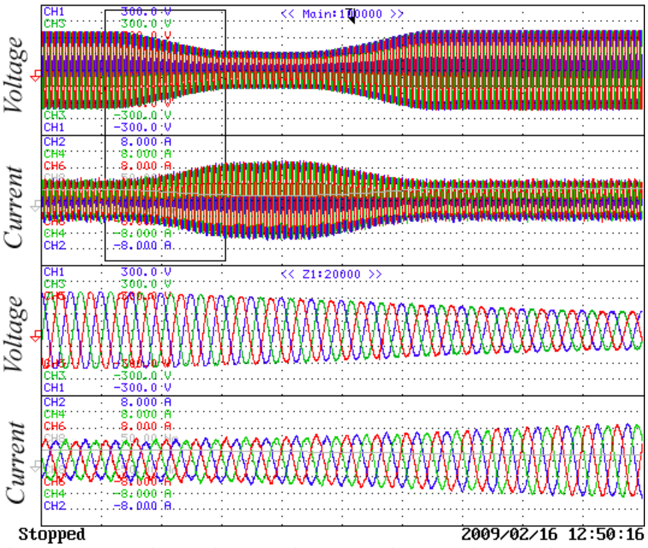

Fig. 11. Stator voltage (above) and currents (down) without implementation of strategy.

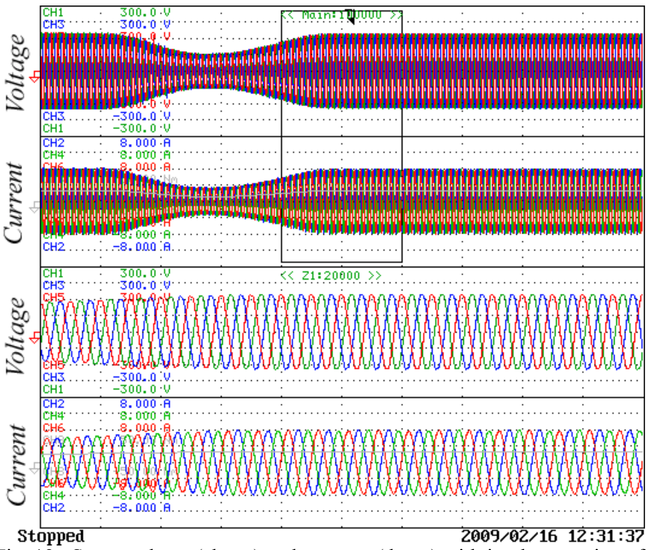

Fig. 12. Stator voltage (above) and currents (down) with implementation of strategy.

In order to produce voltage sag at the point of coupling of the generator, a squirrel cage induction machine (SCIM) was directly connected to the stator windings. The high inrush currents drained by the SCIM produce a voltage drop in the grid, due to the impedance of the network, permitting thus to evaluate the performance of the proposed strategy under such conditions. In this case the depth of the voltage dip is 67%, as shown in Fig. 13, producing the same effect on the stator currents, available in Fig. 14

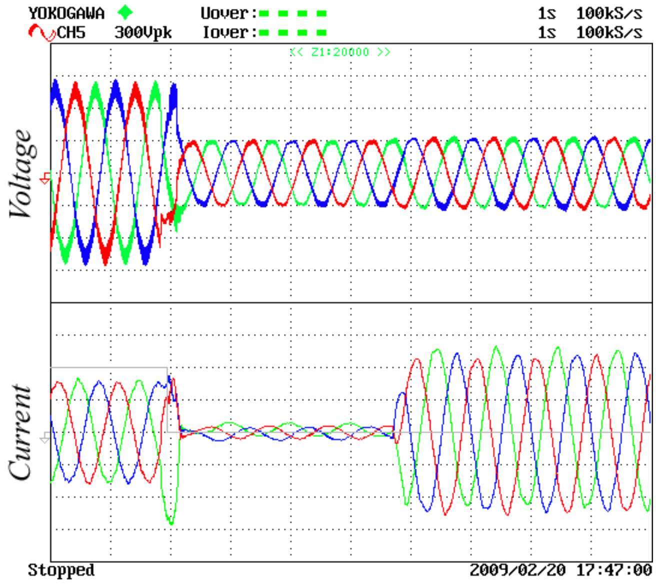

Fig. 13. Stator voltage (above) and currents (down) with implementation of strategy. 50V/div, 2A/div and 20ms/div.

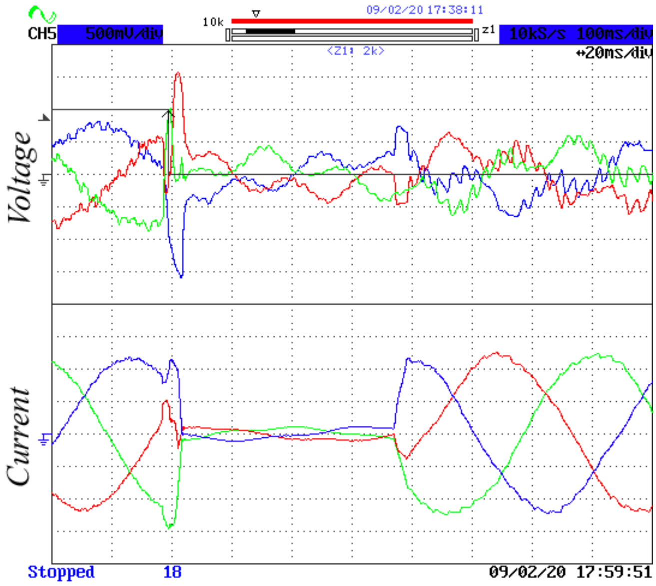

Fig. 14. Rotor voltage (above) and currents (down) with implementation of strategy. 40V/div, 2A/div and 20ms/div.

V. CONCLUSION

In this paper the modeling of a DFIG, considering the behavior of the generator when transients in the stator voltage occur, was developed. Thanks to this model, that permits to predict the performance of a DFIG under faulty scenarios, a novel control strategy for the rotor side controllers, oriented to enhance its response during severe voltage sags, was proposed. This strategy is based on using the measured stator current values as the setpoint for the rotor current controller during the fault. As it has been demonstrated, in this way, it is possible to synthesize a current in the stator in opposition to the currents generated during the fault, preventing thus the stator/rotor windings from suffering overcurrents, with no need of using crowbar circuits.

The analytical equations, the simulation models based on

PSCAD/EMTDC and experimental results have shown that the fluctuations in the stator and rotor currents, as well as in the electromagnetic torque were reduced by the half, when using the new proposed strategy in case of severe balanced and unbalanced voltage sags at the PCC.

Therefore the results presented in this paper, show that it is possible to control the stability of a DFIG during severe contingencies in the power network, without the need of external auxiliary circuits. This issue enables the rotor side power converter to remain connected to the grid in faulty scenarios, without getting damaged, something that, as a difference with applications based on crowbar circuits, permits to implement specific strategies in order to boost the voltage at the PCC during the fault as the new GC demand.

ACKNOWLEDGEMENT

The author would like to aknowledge the financial support received from CNPq, FAPERJ and FINEP.

REFERENCES

[1] S. Seman, J. Niiranen, and A. Arkkio, "Ride-through analysis of doubly fed induction wind-power generator under unsymmetrical network disturbance", *IEEE Transactions on Power Systems,* vol. 21, nº 4, Nov. 2006, pp. 1782–1789.

[2] C. Klumpner and F. Blaabjerg, "Experimental evaluation of ride-through capabilities for a matrix converter under short power interruptions", *IEEE Transaction on Industrial Electronics*, vol. 49, nº 2, April 2002, pp. 315–324.

[3] G. Iwanski and W. Koczara, "DFIG-based power generation system with UPS function for variable-speed applications", *IEEE Transaction on Industrial Electronics*, vol. 55, nº 8, 2008, pp. 3047–3054.

[4] F. Bonnet, P.-E. Vidal, and M. Pietrzak-David, "Dual direct torque control of doubly fed induction machine", *IEEE Transaction on Industrial Electronics*, vol. 54, nº 5, 2007, pp. 2482–2490.

[5] P. S. Flannery and G. Venkataramanan, "A fault tolerant doubly fed induction generator wind turbine using a parallel grid side rectifier and series grid side converter", *IEEE Transaction on Power Electronics*, vol. 23, nº 3, 2008, pp. 1126–1135.

[6] G. Abad, M. A. Rodriguez, and J. Poza, "Two-level VSC based predictive direct torque control of the doubly fed induction machine with reduced torque and flux ripples at low constant switching frequency", *IEEE Transaction on Power Electronics*, vol. 23, nº 3, 2008, pp. 1050–1061.

[7] C. Abbey and G. Joos, "Effect of low voltage ride through (LVRT) characteristic on voltage stability", *IEEE Power Engineering Society General Meeting*, 2005, vol. 2, pp. 1901–1907.

[8] F. M. Hughes, O. Anaya-Lara, N. Jenkins, and G. Strbac, "A power system stabilizer for DFIG-based wind generation", *IEEE Transaction on Power Systems*, vol. 21, issue 2, 2006, pp. 1558–0690.

[9] F. M. Hughes, O. Anaya-Lara, N. Jenkins, and G. Strbac, "Control of DFIG-based wind generation for power network support", *IEEE Transaction on Power Systems,* vol. 20, issue 4, 2005, pp.1958–1966.

[10] B. Xie, B. Fox, and D. Flynn, "Study of fault ride-through for DFIG based wind turbines", *IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*, 2004, vol. 1, 5-8 April 2004, pp. 411–416.

[11] J. Morren and S. W. H. de Haan, "Ride through of wind turbine with doubly-fed induction generator during a voltage dip", *IEEE Transaction on Energy Conversion*, vol. 20, nº 2, 2005, pp. 435–441.

[12] A. Petersson, S. Lundberg, and T. Thiringer, "A DFIG wind-turbine ride-through system influence on the energy production", in *Nordic Wind Power conference, Chalmers University of technology*, Göteborg, 2004.

[13] D. Xiang, L. Ran, P. J. Tavner, and S. Yang, "Control of a doubly-fed induction generator in a wind turbine during grid fault ride-through", *IEEE Transaction on Energy Conversion*, vol. 21, nº 3, 2006, pp. 652–662.

[14] I. Erlich, H. Wrede, and C. Feltes, "Dynamic behavior of DFIG-base wind turbines during grid faults", *Power Conversion Conference*, April 2007, Nagoya, pp. 1195–1200.

[15] J. Morren and S. W. H. de Haan, "Short-circuit current of wind turbines with doubly fed induction generator", *IEEE Transaction on Energy Conversion*, vol. 22, nº 1, March 2007, pp.174–180

[16] M. Rodríguez, G. Abad, I. Sarasola and A. Gilabert, "Crowbar control algorithms for doubly fed induction generator during voltage dips", *2005 European Conference on Power Electronics and Applications,* 11–14 Sept. 2005, 10 pp.

[17] A. Petersson, "Analysis, modeling and control of doubly-fed induction generators for wind turbines", Ph.D. dissertation, Department of Energy and Environment, Chalmers University of Technology, Göteborg, 2005.

[18] B. I. Næss, M. Molinas and T. Undeland, "Laboratory tests of ride through for doubly fed induction generators", in *Nordic Wind Power Conference*, May 22-23, 2006, Espoo, Finland.

[19] W. Leonhard, *Control of Electrical Drives*, Springer, 3rd Edition, New York, 2001.

[20] F. K. A. Lima and E. H. Watanabe, "Parallel connection of doubly-fed induction generator in wind generation", in *9º Power Electronics Brazilian Conference*, 2007, vol. 09, pp. 631–639.