Reactive Power Control of DFIG-Based Wind Turbine during Voltage Sag

Francisco Kleber de A. Lima
Federal University of Ceara
Fortaleza-Ceara, Brazil
email: klima@dee.ufc.br

Joacillo Luz Dantas
Federal Institute of Education,
Science and Technology of Ceara
Fortaleza-Ceara, Brazil
email: joacillo@ifce.edu.br

Carlos Gustavo C. Branco
Federal University of Ceara
Fortaleza-Ceara, Brazil
email: gustavo@dee.ufc.br

***Abstract*—Improving the Fault Ride Through capability (FRT) of Doubly Fed Induction Generators (DFIG) in wind power applications is a very important challenge for wind power industry. The mathematical models of such generators allow to analyze their response under generic conditions. However, their mathematical complexity does not contribute to simplify the analysis of the system under transient conditions, and hence do not help to find straigh-forward solutions to enhance their FRT. This paper discusses an important point that is still absent in the Brazilian grid code. This point is the reactive power injection by the wind turbine during a voltage sag, in order to realize the voltage regulation at the point of common coupling (PCC). The advantages of such requirement to the system will be widely discussed in this work. Furthermore, the simulations and experimental results will also be shown in order to demonstrate the proposed ideas.**

***Index Terms*—Wind energy, energy conversion, power distribution faults, wind power generation.**

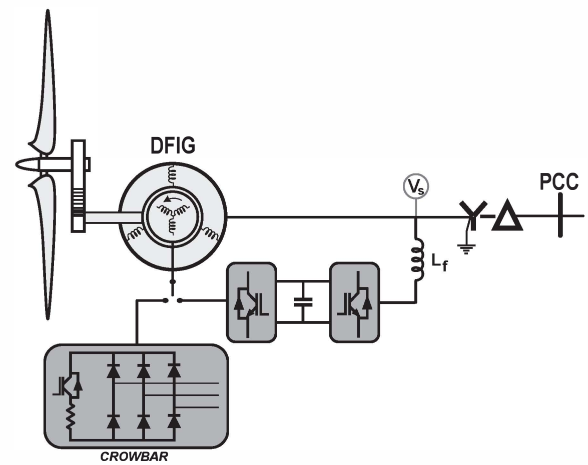

Fig. 1. DFIG-based wind generator connected to the grid.

I. Introduction

Wind power generation have increased significantly during the last years, and nowadays counts on growing markets in Europe, North-America and Asia. The European wind power industry has formulated generation targets of 180 GW in 2020 and 300 GW by the end of 2030. Experiences in countries with high penetration of wind power generation, such as Denmark, Spain or Germany, together with national power system studies, have demonstrated that this scenario is technically and economically feasible. However, the rapid expansion of wind power has made necessary to redesign the existing grid code requirements (GCR). The Transmission System Operators (TSOs) demand now more reliability to wind power technologies and, as consequence, the standards regarding the connection, operation and maintenance of such power plants, are becoming more restrictive. Several countries have issued dedicated grid codes for connecting the wind turbines/farms to the electrical network addressed to transmission and/or distributed system. In most of the cases, these requirements have focus on power controllability, power quality and fault ride-through capability. Some grid codes have gone even further, and require also grid support during network disturbances, like in the German and Spanish case.

At the present time, variable speed wind turbines based on doubly fed induction generators (DFIG) and controlled by means of back to back power converters constitute almost the 50% of the installed WTs worlwide in on-shore wind farms [1]. The layout of a WT based on this technology is shown in Fig. 1. As explained in [2], the success of this kind of WTs lies in the fact that it offers a good solution for controlling the active and reactive power generation in a reasonable + 30% range of the generator's nominal power.

Despite the fact that the operation of DFIG-WTs is satisfactory under grid balanced conditions, its performance is not so good when the voltage at the point of common coupling (PPC) is affected by voltage sags or network imbalances. Under such conditions, the electromagnetic transient of the DFIG give rise to high overcurrents in the converter, which may produce its disconnection in order to avoid damages in the semiconductors. This operation mode prevents DFIG-WT's from fulfilling the requirements regarding the FRT capability of grid connected WTs, as no possible control can be carried out if the converter is tripped.

In some countries, especially those which have always been at the forefront of the exploitation of wind energy, the penetration of wind generation is already such that the wind turbine during a fault should not only stay connected, but also control the reactive power in order to support the voltage at point of common coupling [3], [4], [5].

978-1-4673-2421-2/12/$31.00 ©2012 IEEE

The following, this paper will show how the reactive current injection or, in other words, as the capacitive reactive power control can improve the dynamics of the voltage at PCC after the clearance of the voltage sag for DFIG-based wind turbine systems.

II. Reactive Power Injection during Fault Ride-Through

The control of the system currents is only part of the solution of the LVRT problem, since the majority of new grid codes require the control of reactive power in order to support the restoration of the voltage at the connection point. Thus, besides the proposed strategy for the current control, a technique to control the reactive power that allows the wind turbine to fulfill the grid fault ride-through requirements should be implemented by the wind generation system.

Why is it important to inject reactive power during a voltage sag?

Well, there are two ways to answer this question. One of them concerns the fact that usually in the power system there are a lot of induction motors connected, and during a severe voltage sag these motors are strongly demagnetized because the stator voltage decreased and also decelerated.

Later, during the sag clearance the grid voltage is established and, eventually, induction motors connected at the PCC drain from the system a too large magnetizing current. This current can force the voltage at the point of common coupling have a new collapse.

However, if during the voltage sag the wind turbine generates capacitive reactive power, as shown in Fig. 2 when the voltage sag finishes, the magnetization of the motors may occur more smoothly having smaller impact in the power quality at the PCC.

And the other one, some current studies show there is influence of the reactive power injected into the grid from wind power turbines during a severe voltage sag on the operation of wind turbine circuit breaker.

Studies as published in [6] show that if the passive crowbar protection has high crowbar resistance, the zero crossing of the circuit breaker current is delayed. This fact has influence on the operation of the circuit breaker since the breaker can interrupt the current only when the current crosses zero.

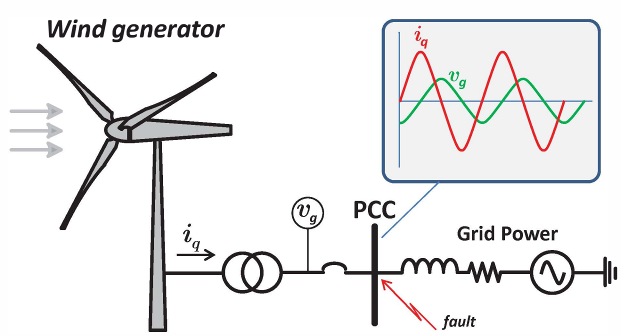

Fig. 2. Reactive (capacitive) power control during voltage sag.

So, if there is no zero crossing an arc appears between the breaker contacts. Especially at medium voltage levels the zero crossing of the current is attained earlier due to the resistance of the arc. If the wind turbine is connected to the high voltage level and the fault near the turbine occurs the arc resistance is not so effective in decreasing the delay of the currents zero crossings.

Summarizing, the new grid codes require that wind turbines generates capacitive reactive current to the grid during a voltage sag. It can be shown that the reactive current injection:

- When the wind turbine must remain connected to the grid, contributes to the magnetization of the motors may occur more smoothly having smaller impact in the power quality at the PCC;
- When the wind turbine needs to be disconnected from the grid, it adds extra oscillations on the circuit breaker currents. These oscillations accelerates the current zero crossings and thus improves the operation of the circuit breaker. In other words, the reactive current injection can contribute to the operation of wind turbine circuit breaker increasing their effectiveness, in case of necessity to disconnect the wind turbine. It is important to keep in mind that if it is the last long fault the turbine must be disconnected.

However, the main objective of this paper is also to show the improvement in the dynamic behavior of the post-fault transient stator currents with capacitive current injection.

The Brazilian grid code still does not require the reactive current injection from the wind turbine during a voltage sag.

III. The DFIG Reactive Power

The steady state equation of the stator currents in dq synchronous reference frame as function of rotor currents, described in [7], are depicted by:

$$I_{sd}(s) = \frac{1}{L_s \omega_s} V_{sq} - \frac{L_m}{L_s} I_{rd}, \tag{1}$$

$$I_{sq}(s) = \frac{R_s}{L_s^2 \omega_s^2} V_{sq} - \frac{L_m}{L_s} I_{rq}. \tag{2}$$

By means of analyzing (2), it can be concluded that the multiplicative factor of the in-quadrature component of the stator's voltage tends to zero. Therefore, and considering that, this equation can be reduced to:

$$I_{sq}(s) = -\frac{L_m}{L_s} I_{rq}. \tag{3}$$

The reactive power of the stator is defined by:

$$q_s = v_{sd} i_{sq} - v_{sq} i_{sd}. \tag{4}$$

Considering that the q-axis parcel of the stator voltage is null (d-axis aligned to stator flux vector), we will have:

$$q_s = -v_{sq} i_{sd}. \tag{5}$$

The handling of the equations above allows us to reach:

$$q_s = -\frac{v_{sq}^2}{\omega_s L_s} + \frac{L_m}{L_s} v_{sq} i_{rd}. \qquad (6)$$

Assuming the stator voltage amplitude and frequency constant from (6) show that it is possible to control the reactive power stator, by controlling the direct current component of the rotor.

Equation (6) can be rewritten as:

$$q_s = -\frac{L_m}{L_s}\left(\underbrace{\frac{v_{sq}^2}{\omega_s L_m}}_{\substack{\text{magnetizing}\\ \text{reactive}\\ \text{power}}} - v_{sq} i_{rd} \right). \qquad (7)$$

The final value of q_s in (7) depends upon two terms. The first one, considering the steady state conditions, describes the magnetizing reactive power.

So, this means that the magnetizing reactive power of the machine depends on the stator voltage. Soon after the grid fault the machine needs reactive power and this will cause increase of both the stator and rotor currents. But, if is possible to provide this reactive energy to the machine through the control system, the rotor and stator currents will not suffer significant increases.

IV. Simulation Results

In this section, in order to validate the proposed ideas in this paper simulation results have been collected using PSCAD/EMTDC using a DFIG complete order model constructed in that simulator. The machine parameters used for that simulation are shown in Table I.

TABLE I
SPECIFICATION OF THE SIMULATED SYSTEM.

DFIG Characteristics	Values
Rated power	100 kVA
Rated stator voltage	220 V
Rated rotor voltage	220 V
Rated stator frequency	60 Hz
Stator resistance	2.6 mΩ
Rotor resistance	2.9 mΩ
Stator leakage inductance	138.66 μH
Rotor leakage inductance	141.22 μH
Magnetizing inductance	5.6 mH
Angular moment of inertia (J=2H)	0.5 pu
Poles pairs	1

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 25% depth balanced voltage sag at the stator winding occurs at t = 3s and last after 500ms.

A balanced voltage sag is shown through its aggregated value, in Fig. 3, and abc coordinates values in Fig. 4.

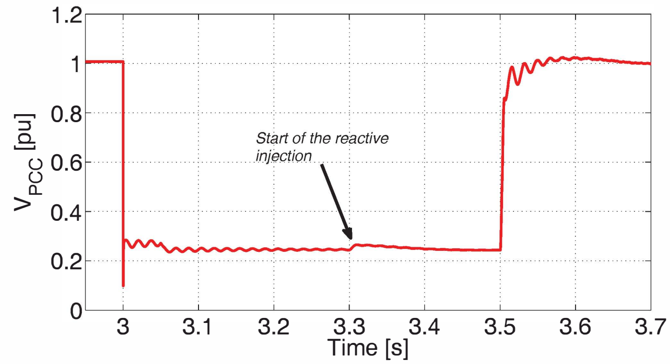

Fig. 3. Voltage at the point of common coupling.

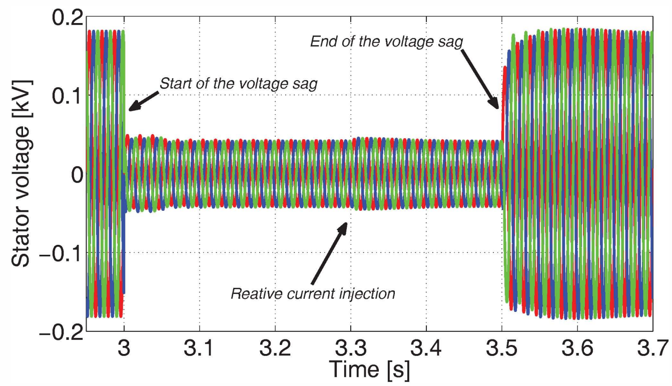

Fig. 4. Stator voltage in abc coordinates.

In these figures is also possible to observe the just moment of injection of capacitive reactive current. From this moment, the value of the stator voltage undergoes a slight increase.

It can seen that after the sag clearance both the stator and rotor currents suffer increases to levels that could compromise the system.

Figures 5 and 6 shows the stator and rotor current behaviors during balanced voltage sag when the power reactive control is not enable. In this figures is possible to see the increasing of the stator and rotor currents after que sag clearance.

On the other hand, when the reactive power control is

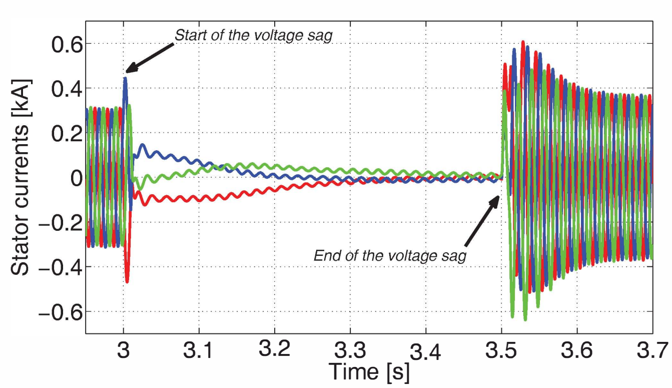

Fig. 5. Stator currents during balanced voltage sag without reactive power control.

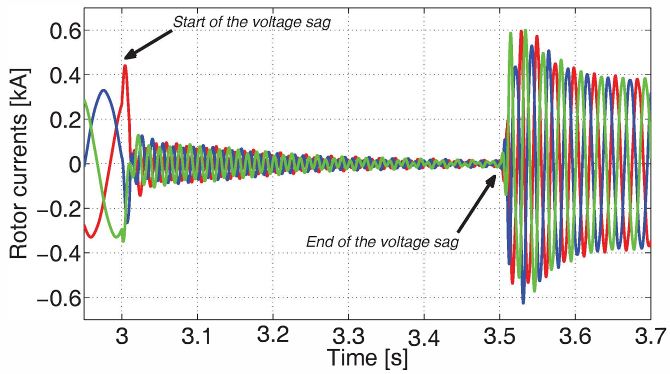

Fig. 6. Rotor currents during balanced voltage sag without reactive power control.

enabled through the control system, the behavior for both the stator and rotor currents after the voltage sag is very different. The current increases is not observed for this case. This effect can be seen in Fig. 7 and Fig. 8.

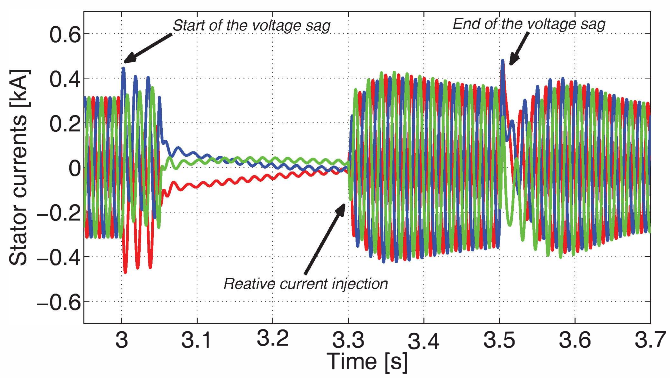

Fig. 7. Stator currents during balanced voltage sag with reactive power control.

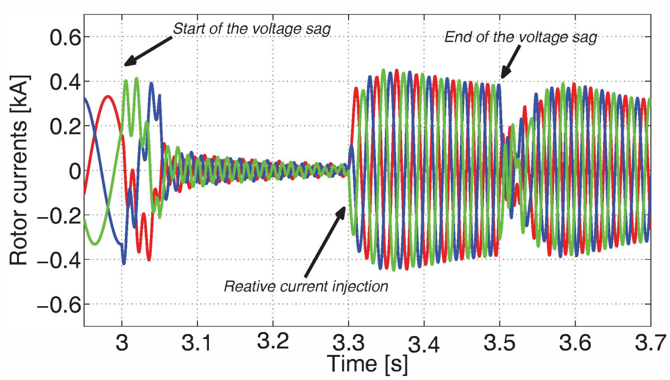

Fig. 8. Rotor currents during balanced voltage sag with reactive power control.

Since the reactive power required to magnetize the machine after the fault was provided during the sag, the machine starting current was greatly damped, does not represent a problem for the system after the grid fault.

V. Experimental Results

The performance of the presented idea has been tested in a scaled experimental setup, where not only the capability for reducing the rotor currents under fault conditions with the proposed strategy has been tested, but also the reactive current injection, as well as the evolution of the stator and rotor currents has been monitored. Table II gathers the parameters of the doubly-fed induction generator used in the experimental tests of this paper.

TABLE II
SPECIFICATION OF THE EXPERIMENTAL SETUP.

DFIG Characteristics	Values
Rated power	7.5 kVA
Rated stator voltage	220 V
Rated rotor voltage	220 V
Rated stator frequency	50 Hz
Stator resistance	0.462 mΩ
Rotor resistance	0.473 mΩ
Stator leakage inductance	3.93 μH
Rotor leakage inductance	3.93 μH
Magnetizing inductance	103.4 mH
Turns ratio	1
Poles pairs	2

Figures 9 and 10 shows the stator and rotor current behaviors from a wind turbine experimental setup. For this case, it not was implemented the reactive power control, so, it is possible to observe the increasing on stator and rotor currents after the sag clearance.

Figure 11 and 12 shows the reactive current injection from a wind turbine experimental setup. So, some milliseconds after the start of voltage sag the stator and rotor currents already are perfectly controlled and the control system starts the reactive current injection, as can be seen in Fig. 11.

As the voltage at the PCC is below the nominal value during the sag, the control system should control the capacitive

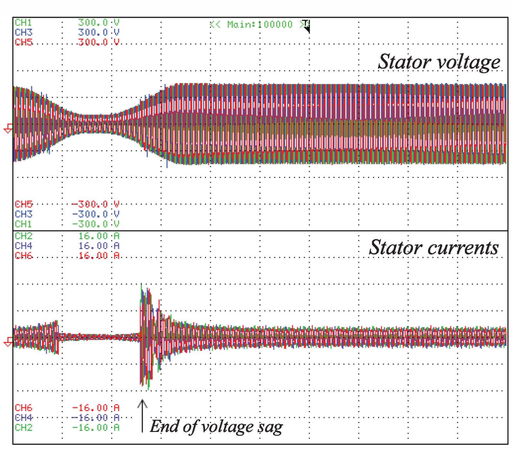

Fig. 9. Stator voltage and current. Without reactive power control during voltage sag.

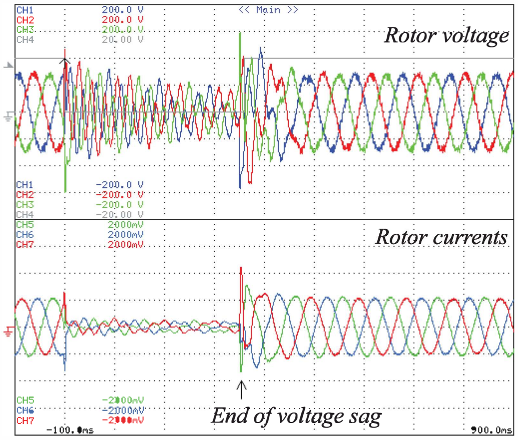

Fig. 10. Rotor voltage and current. Without reactive power control during voltage sag.

reactive power at the PCC. This means that the injected current must be 90^o leading with respect to the PCC voltage.

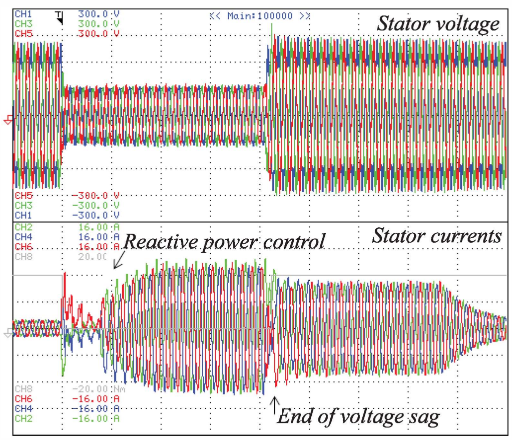

Fig. 11. Stator voltage and current. With reactive power control during voltage sag.

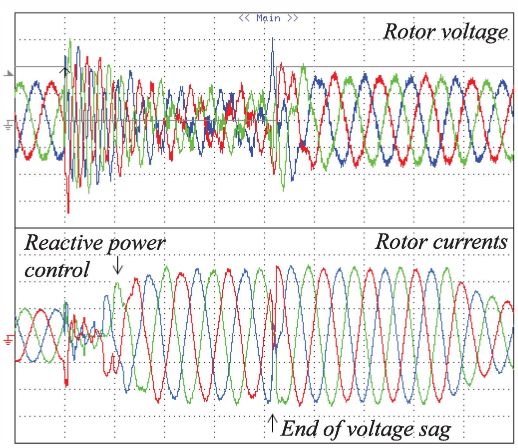

Fig. 12. Rotor voltage and current. With reactive power control during voltage sag.

The comparison between the results shown in Figs. 9 and 10 (system without reactive control), and Figs. 11 and 12 (system with reactive control), show that the injection current reactive (capacitive reactive power control) contributes to the currents of both the stator and the rotor does not undergo important increases after the sag clearance.

VI. Conclusion

The use of wind energy presents lots of advantages as it is renewable and clean energy. However, some problems exists in the interconnections of this kind of energy into the grid. This paper took just two possible problems and analyzed it. The first problem analyzed was the low voltage ride through (LVRT) capability for wind generator based on DFIG (Doubly-Fed Induction Generator).

The reactive power control during a voltage sag on DFIG based wind turbines was also analyzed. It can be seen that from the point of view of the turbine the current increases after the fault clearance. Furthermore, it was shown that the capacitive reactive power control contributes to the proper behavior of the DFIGs currents. This has an important impact for the PCC voltage especially in weak networks, because in this case, in the moments immediately after the fault clearance it could suffer a new sag due to the substantial increase in the wind turbine currents.

Acknowledgment

The authors would like to thank the National Counsel of Technological and Scientific Development - CNPq (554578/2010-7) for their financial support for the development of this work.

References

[1] F. Blaabjerg and Z. Chen, *Power Electronics for Modern Wind Turbines*, 1st ed. United States of America: Morgan & Claypool Publishers, 2006.

[2] S. Müller; M. Deicke & R. W. De Doncker. "Doubly fed induction generator systems for wind turbines", *IEEE Ind. Appl. Magazine*, Vol., No., May/June 2002, 26-33, ISSN 1077-2618/02.

[3] A. Morales, X. Robe, M. Sala, P. Prats, C. Aguerri, and E. Torres, "Advanced Grid Requirements for the Integration of Wind Farms into the Spanish Transmission System", *IET Renewable Power Generation*, vol. 2, n^o 1, Mar. 2008, pp. 47-59.

[4] E-ON Netz GmbH, "Grid Code - High and Extra High Voltage", Apr. 2006, <http://www.eon-netz.com>.

[5] National Grid Electricity Transmission, "The Grid Code: Revision 31", *in United Kingdom* n^o 3, Oct. 2008, <http://www.nationalgrid.com/uk>.

[6] A. S. Mäkinen, O. Raipala, S. Repo, and H. Tuusa, "Influence of DFIG Reactive Current Injection during a Voltage Dip on the Operation of Wind Turbine Circuit Breaker", in *8th International Conference on Power Electronics - ECCE Asia*, May 88-95, 2011, The Shilla Jeju, Korea.

[7] F. K. A. Lima, A. Luna, P. Rodríguez, E. H. Watanabe, and F. Blaabjerg, "Rotor Voltage Dynamics in the Doubly Fed Induction Generator During Grid Faults", *IEEE Transaction on Power Electronics*, vol. 25, n^o 1, Jan 2010, pp. 118-130.