

A DEADBEAT CONTROLLER FOR DOUBLY-FED INDUCTION GENERATOR POWER CONTROL

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Abstract - A deadbeat power control scheme for doubly-fed induction generator for variable speed was proposed. The deadbeat controller algorithm calculates the voltage vector to be supplied to the rotor in order to eliminate the active and reactive power errors in each period using and stator field orientation and the doubly-fed induction generator dynamic model. The deadbeat controller uses the rotor current control to the power control of the machine. This control technique can be applied to the wind energy systems. Experimental results are carried out to validate of the deadbeat controller operation.

Keywords – Doubly-fed Induction Generator, Deadbeat Control, Power Control, Variable Speed Constant Frequency Applications.

I. INTRODUCTION

The renewable energy systems and specially wind energy have attracted interest due to the increasing concern about CO₂ emissions. The wind energy systems using a doubly-fed induction generator (DFIG) have some advantages due to variable speed operation and four quadrant active and reactive power capabilities compared with fixed speed induction generators and lower cost when compared with solar energy [1, 2].

In wind energy systems the stator of DFIG is direct connected to the grid and the rotor links the grid by a bi-directional converter as shown in Figure 1. The rotor converter objective aims to the DFIG active and reactive power control between the stator and ac supply.

The power control of DFIG is traditionally based on either stator-flux-oriented [3] or stator-voltage-oriented [4] vector control. Some investigations using PI controllers that generates reference currents from active and reactive power errors to the inverter or a cascade PI controllers that generate a rotor voltage which have been presented by [3, 5–7]. The problem in the use of PI controller is the tuning of the gains and the cross-coupling on DFIG terms. An interesting method to solve these problems have been presented by [8–10].

Some investigations for DFIG power control by using predictive functional controller [11], internal mode controller [12, 13] and predictive control [14, 15] have satisfactory power response when compared with the power response of PI but it is hardly to implement one due to the formulation of the controllers.

To improve the power response and to protection of rotor-side converter under grid voltage sags with stator voltage orientation a proportional control with anti-jamming control which has been proposed by [16]. This control has satisfactory power response and eliminate the rotor current overshoot in voltage sags although power and rotor currents results was shown only in super-synchronous DFIG operation and the proportional controller needs to be carefully tuned to ensure system stability and adequate response within the whole operating range.

This paper proposes an alternative solution to power control presented in [17] by using the doubly-fed induction generator dynamic discrete equations when DFIG operates with variable speed. The deadbeat control for DFIG power control aims the active and reactive power control using the DFIG dynamic equations in synchronous coordinate system using the stator flux position. The controller calculates the rotor voltages required to guarantee active and reactive power reach their desired reference values in a few sampling intervals in which simulations results were presented in [18]. The deadbeat controller uses the rotor current control to the power control of the machine. This power control technique can be applied to the DFIG for wind energy systems due to the fact the wind speed is uncertain and the controller also operates with variable speed. Experimental results are presented to validate of the proposed controller.

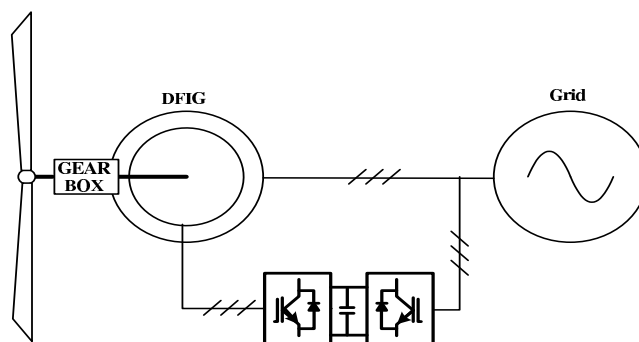


Fig. 1. Configuration of DFIG connected direct on grid.

II. MACHINE MODEL AND VECTOR CONTROL

Doubly-fed induction machine model in synchronous reference frame is given by

$$\vec{v}_{1dq} = R_1 \vec{i}_{1dq} + \frac{d\vec{\lambda}_{1dq}}{dt} + j\omega_1 \vec{\lambda}_{1dq} \quad (1)$$

$$\vec{v}_{2dq} = R_2 \vec{i}_{2dq} + \frac{d\vec{\lambda}_{2dq}}{dt} + j(\omega_1 - NP\omega_{mec}) \vec{\lambda}_{2dq} \quad (2)$$

Manuscript received 06/07/2011; revised 09/11/2011. Accepted for publication 23/11/2011 by recommendation of the Editor Prof. João Onofre Pereira Pinto.

the relationship between fluxes and currents

$$\vec{\lambda}_{1dq} = L_1 \vec{i}_{1dq} + L_M \vec{i}_{2dq} \quad (3)$$

$$\vec{\lambda}_{2dq} = L_M \vec{i}_{1dq} + L_2 \vec{i}_{2dq} \quad (4)$$

and generator active and reactive power are

$$P = \frac{3}{2} (v_{1d} i_{1d} + v_{1q} i_{1q}) \quad (5)$$

$$Q = \frac{3}{2} (v_{1q} i_{1d} - v_{1d} i_{1q}) \quad (6)$$

where \vec{v} , \vec{i} , $\vec{\lambda}$ are voltage, currents and flux space vectors, respectively, R is resistance of the winding, L is inductance of the winding, the subscripts 1, 2, M denotes stator, rotor and mutual, NP is the pole pairs and ω_{mec} is the rotor speed. The parameters estimation of the induction machine were made using the method presented in [19].

The DFIG power control aims independent stator active P and reactive Q power control by means a rotor current regulation. For this purpose, P and Q are represented as functions of each individual rotor current space vector components. Using stator flux oriented control, that decouples dq axis (3) becomes

$$i_{1d} = \frac{\lambda_1}{L_1} - \frac{L_M}{L_1} i_{2d} \quad (7)$$

$$i_{1q} = -\frac{L_M}{L_1} i_{2q} \quad (8)$$

and the active (5) and reactive (6) power can be calculated by using Equations (7) and (8) and it is given by

$$P = -\frac{3}{2} v_1 \frac{L_M}{L_1} i_{2q} \quad (9)$$

$$Q = \frac{3}{2} v_1 \left(\frac{\lambda_1}{L_1} - \frac{L_M}{L_1} i_{2d} \right) \quad (10)$$

Thus, rotor currents will reflect in stator currents and on stator active and reactive power. Consequently, this principle can be used on stator active and reactive power control by using current control on rotor side of the DFIG with stator direct connected to the grid.

A. Rotor Side Equations

The control of rotor currents allows the DFIG power control as can be seen in (9) and (10). The rotor voltage (2), in the synchronous referential frame using the stator flux position, Equations (7) and (8) becomes

$$\vec{v}_{2dq} = (R_2 + jL_2\omega_{sl}) \vec{i}_{2dq} + jL_m\omega_{sl} \vec{i}_{1dq} + \left(L_2 - \frac{L_M^2}{L_1} \right) \frac{d\vec{i}_{2dq}}{dt} \quad (11)$$

where $\omega_{sl} = \omega_1 - P\omega_{mec}$.

In space state form (11) becomes

$$\frac{d\vec{i}_2}{dt} = H \vec{i}_2 + K \vec{v}_2 + L \vec{i}_1 \quad (12)$$

$$\begin{bmatrix} \frac{di_{2d}}{dt} \\ \frac{di_{2q}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-R_2}{\sigma L_2} & \frac{\omega_{sl}}{\sigma} \\ \frac{-\omega_{sl}}{\sigma} & \frac{-R_2}{\sigma L_2} \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_2} & 0 \\ 0 & \frac{1}{\sigma L_2} \end{bmatrix} \begin{bmatrix} v_{2d} \\ v_{2q} \end{bmatrix} + \begin{bmatrix} 0 & \frac{\omega_{sl} L_M}{\sigma L_2} \\ \frac{-\omega_{sl} L_M}{\sigma L_2} & 0 \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} \quad (13)$$

where $\sigma = 1 - \frac{L_M^2}{L_1 L_2}$.

From now it will be assumed that the mechanical time constant is much greater than the electrical time constants. Thus $\omega_{mec} = \text{constant}$ is a valid approximation for each sampling time. As synchronous frequency is fixed by the grid, slip speed $\omega_{sl} = \text{constant}$ for each sampling time is also a valid approximation.

III. THE DEADBEAT CONTROL

The deadbeat control is a digital control technique that allows to calculate required input $\vec{u}(k)$ to guarantee that the output $\vec{x}(k)$ will reach their desired reference values in the smallest number of sampling intervals using a discrete equation of the continuous linear system which have been presented in [20]. For an N th-order linear system, the minimum number of steps (sampling intervals) will be at most N to the output reaches their desired reference values [20].

A linear continuous system is represented by

$$\begin{aligned} \dot{\vec{x}} &= A\vec{x} + B\vec{u} + G\vec{w} \\ \vec{y} &= C\vec{x} \end{aligned} \quad (14)$$

where \vec{w} denotes the perturbation vector and A , C , B and G $n \times n$ matrices. In this paper $C = I$, where I is the identity matrix.

The Equation (14) can be discretized considering T as the sampling period and k as the sampling time by using zero-order-hold (ZOH) with no delay as

$$\vec{x}(k+1) = A_d \vec{x}(k) + B_d \vec{u}(k) + G_d \vec{w}(k) \quad (15)$$

where

$$\begin{aligned} A_d &= e^{AT} \cong I + AT \\ B_d &= \int_0^T e^{A\tau} B d\tau \cong BT \\ G_d &= \int_0^T e^{A\tau} G d\tau \cong GT \end{aligned} \quad (16)$$

The input calculation to guarantee a null steady state error is given by

$$\vec{u}(k) = F (\vec{x}_{ref} - \vec{x}) \quad (17)$$

where \vec{x}_{ref} is the reference vector and F is the matrix gain.

Substituting (17) in (15) and making $\vec{x}_{ref} = \vec{x}(k+1)$ the input that guarantees a null steady state error is given by

$$\vec{u}(k) = \underbrace{B_d^{-1} A_d}_{F} [A_d^{-1} \vec{x}(k+1) - \vec{x}(k) - A_d^{-1} G_d \vec{w}(k)] \quad (18)$$

The block diagram that represents (17) is shown in Figure 2

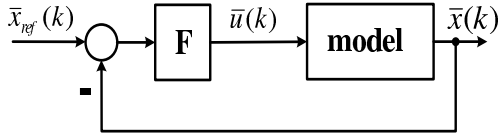


Fig. 2. Deadbeat block diagram.

A. Deadbeat Power Control

The power control scheme uses a deadbeat controller presented in section III to obtain rotor voltages which should be applied on generator in order to guarantee active and reactive power reach their desired reference values in N samplings intervals. The sampling period T has the same time of PWM modulator. The converter that is connected to the grid control the voltage of the link DC and one can be controlled by using a current control [21]. The deadbeat power control block diagram is shown in Figure 3.

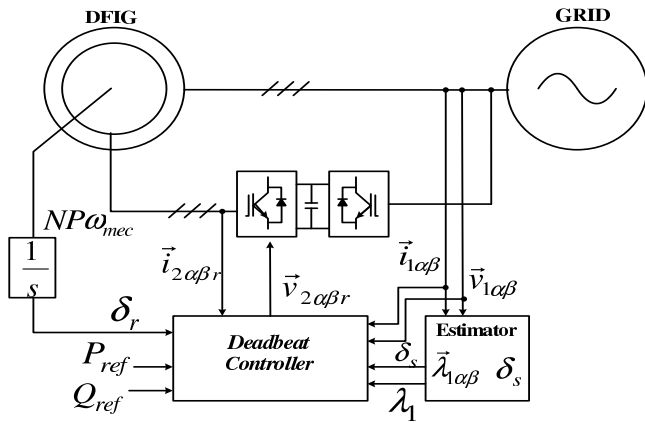


Fig. 3. Deadbeat power control block diagram.

The rotor equation (13) can be rewritten as a discrete equation using (15) and making $\bar{x} = \bar{i}_2$, $A = H$, $B = K$, $\bar{u} = \bar{v}_2$, $G = L$ and $\bar{w} = \bar{i}_1$. It is given by equation (19)

$$\begin{bmatrix} i_{2d}(k+1) \\ i_{2q}(k+1) \end{bmatrix} = \begin{bmatrix} 1 - \frac{R_2 T}{\sigma L_2} & \frac{\omega_{sl} T}{\sigma} \\ -\frac{\omega_{sl} T}{\sigma} & 1 - \frac{R_2 T}{\sigma L_2} \end{bmatrix} \begin{bmatrix} i_{2d}(k) \\ i_{2q}(k) \end{bmatrix} + \begin{bmatrix} \frac{T}{\sigma L_2} & 0 \\ 0 & \frac{T}{\sigma L_2} \end{bmatrix} \begin{bmatrix} v_{2d}(k) \\ v_{2q}(k) \end{bmatrix} + \begin{bmatrix} 0 & \frac{\omega_{sl} L_M T}{\sigma L_2} \\ -\frac{\omega_{sl} L_M T}{\sigma L_2} & 0 \end{bmatrix} \begin{bmatrix} i_{1d}(k) \\ i_{1q}(k) \end{bmatrix} \quad (19)$$

The rotor voltage which is calculated to guarantee null steady state error by using (18) and (19) is given by

$$v_{2d}(k) = \sigma L_2 \frac{i_{2dref} - i_{2d}(k)}{T} + R_2 i_{2d}(k) - L_2 \omega_{sl} i_{2q}(k) - L_M \omega_{sl} i_{1q}(k) \quad (20)$$

$$v_{2q}(k) = \sigma L_2 \frac{i_{2qref} - i_{2q}(k)}{T} + R_2 i_{2q}(k) + L_2 \omega_{sl} i_{2d}(k) + L_M \omega_{sl} i_{1d}(k) \quad (21)$$

For the active power control, the reference of quadrature component of rotor current space vector is achieved by using

Equation (9) is given by

$$i_{2q}(k+1) = i_{2qref} = -\frac{2P_{ref}L_1}{3v_1L_M} \quad (22)$$

and for the reactive power control the reference of direct component of rotor current space vector is achieved by using Equation (10) is

$$i_{2d}(k+1) = i_{2dref} = -\frac{2Q_{ref}L_1}{3v_1L_M} + \frac{\lambda_1}{L_M} \quad (23)$$

The block diagram for deadbeat power control implementation is shown in Figure 4.

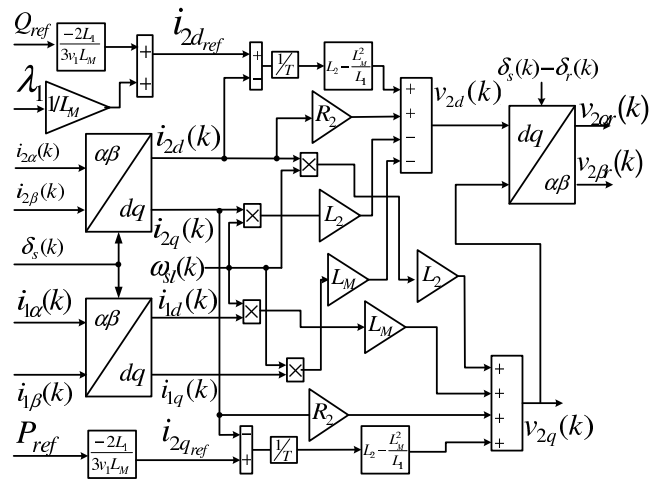


Fig. 4. Deadbeat power control block diagram for implementation.

Thus, if the d and q axis rotor voltage components are calculated according equations (20) and (21) above are applied to the generator, then the active and reactive power convergence to their respective commanded values will occur in a few sampling intervals. The desired rotor voltage in the rotor reference frame ($\delta_s - \delta_r$) generates switching signals for the rotor side using either space vector modulation.

Stator currents and voltages, rotor speed and currents are measured to stator flux position δ_s and magnitude λ_1 , synchronous frequency ω_1 and slip frequency ω_{sl} estimation.

B. Estimation

To deadbeat power control, as show in the equation (21), it is necessary to calculate the active and reactive power values, their errors, the stator flux magnitude and position, the slip speed and synchronous frequency.

The flux estimation using (1) is given by

$$\vec{\lambda}_{1\alpha\beta} = \int (\vec{v}_{1\alpha\beta} - R_1 \vec{i}_{1\alpha\beta}) dt \quad (24)$$

This expression has been implemented for low speed operation in [22] based on method presented in [23] using the block diagram shown in Figure 5.

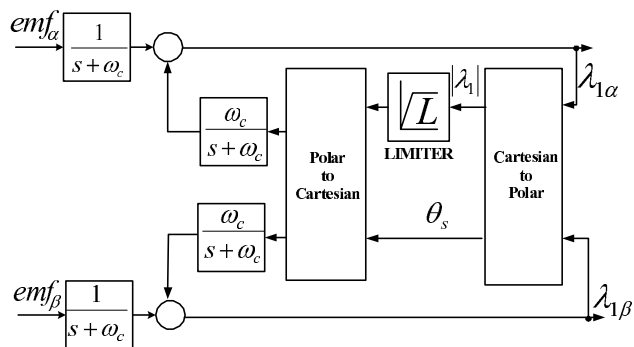


Fig. 5. Block diagram for stator flux estimation.

The flux position by using equation (24) as

$$\delta_s = \arctan\left(\frac{\lambda_{1\beta}}{\lambda_{1\alpha}}\right) \quad (25)$$

The synchronous speed ω_1 estimation is given by

$$\omega_1 = \frac{d\delta_s}{dt} = \frac{(v_{1\beta} - R_1 i_{1\beta}) \lambda_{1\alpha} - (v_{1\alpha} - R_1 i_{1\alpha}) \lambda_{1\beta}}{(\lambda_{1\alpha})^2 + (\lambda_{1\beta})^2} \quad (26)$$

and the slip speed estimation by using the rotor speed and synchronous speed is

$$\omega_{sl} = \omega_1 - NP\omega_{mec} \quad (27)$$

The rotor angle in rotor reference frame is given by

$$\delta_s - \delta_r = \int \omega_{sl} dt \quad (28)$$

IV. EXPERIMENTAL RESULTS

The deadbeat control strategy was implemented using a Texas Instruments DSP TMS320F2812 platform and also has a $T = 4 \cdot 10^{-4} s$. The system consists of a three-phase voltage source inverter with insulated-gate bipolar transistors (IGBTs) and the three-phase doubly-fed induction machine shown in the appendix. The stator voltage commands are modulated by using symmetrical space vector PWM, with switching frequency equal to 2.5 kHz. The DC bus voltage of the inverter is 36 V due to the fact the transformation relationship between stator winds and rotor winds is not one and it is used a transformer between the converter and the grid. The stator voltages and currents are sampled in the frequency of 2.5 kHz. The encoder resolution is 3800 pulses per revolution. The rotor voltage was limited using limiters in the dsp (digital signal processor) program. The speed is applied to the DFIG using a separately excited DC motor in open loop voltage control. The DFIG synchronization is made using the methods presented by [24–27]. The experimental setup is shown in Figure 6.

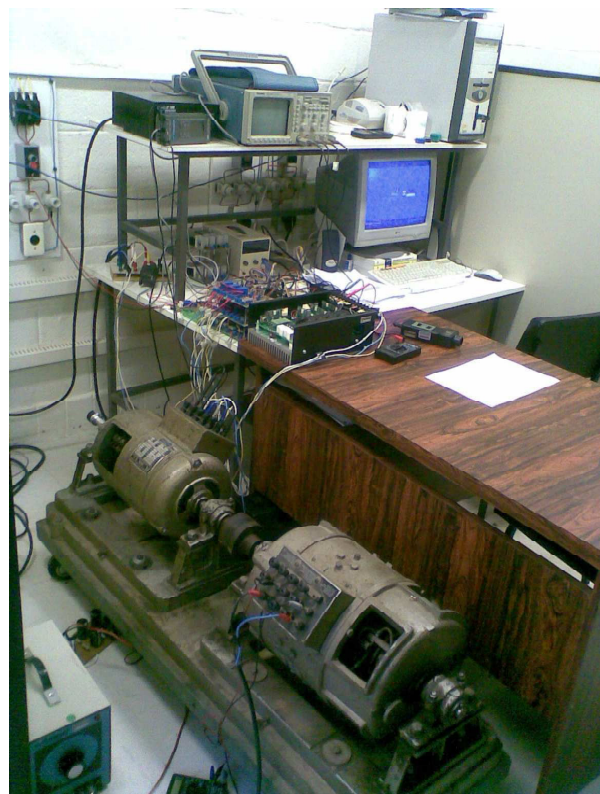


Fig. 6. Experimental setup.

Six tests were made, five in sub-synchronous speed operation and one in several speed operation. The first one was the response of i_{2d} step of 5 A which is shown in Figure 7. The satisfactory performance of controller can be seen due to the fact the reference is followed. In this test the i_{2q} is 0.5A. The rotor current reach the reference no more than 40 ms.

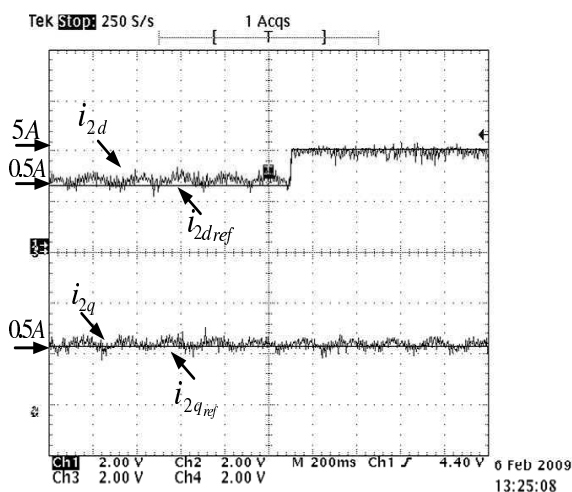


Fig. 7. Response of step test for i_{2d} .

The second was the response of i_{2q} step of 5 A. The satisfactory performance of controller in this test can be seen again in Figure 8 due to the fact the reference is followed. In this test i_{2d} is 4A.

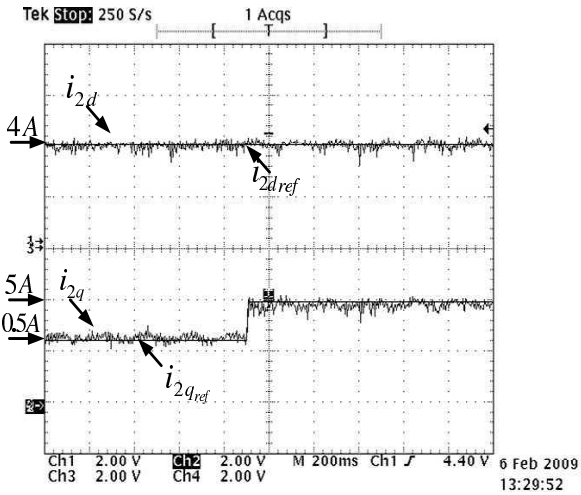


Fig. 8. Response of step test for i_{2q} .

The same test of i_{2q} step of 5 A with rotor currents in rotor reference frame is presented in Figure 9. The satisfactory response of the controller can be seen due to the fact the reference is followed.

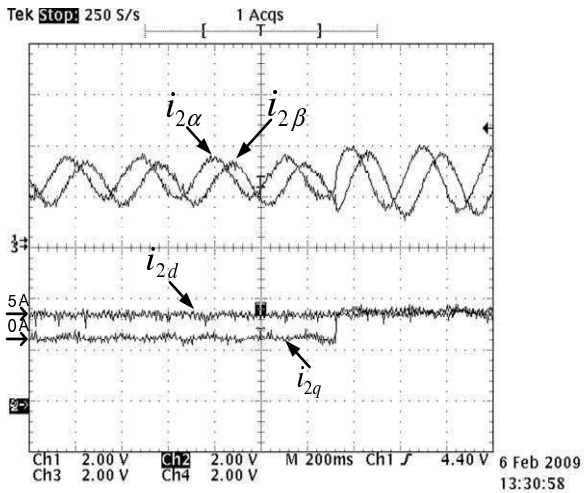


Fig. 9. Response of step test for i_{2q} and rotor currents ($1.4A/div$).

The fourth test is the response of reactive power Q_{ref} of -300 VA , 300 VA and 0 VA which means lag, lead and unitary power factor. The satisfactory performance of the controller is can be seen again in Figure 10 due to the fact the reference is followed. The rotor currents are shown in Fig 11.

The fifth test is the steady state of unitary power factor and active power is $-300W$. The rotor current reference are also calculated using Equations (22) and (23). The response of stator power and rotor current are presented in Figures 12 and 13, respectively. The stator voltage ($127V_{rms}$) and the stator current ($0.8Arms$) of phase α is shown in Figure 14. It can be seen the satisfactory performance of the controller due to the fact the angle between the stator voltage and the stator current is 180° . The spikes occurs due to the fact the noise of the system and errors of measurements currents and voltages.

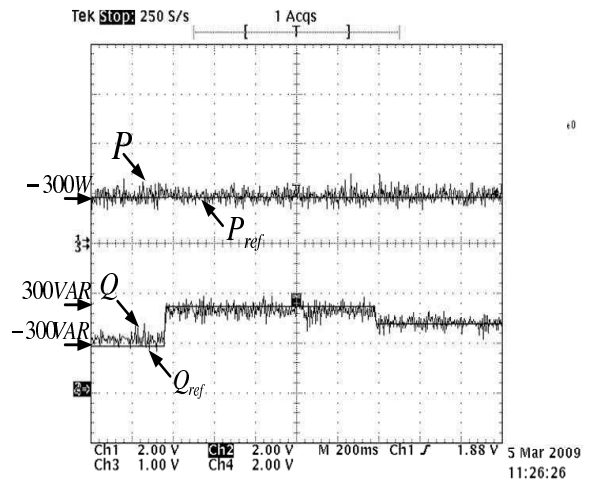


Fig. 10. Response of step test of reactive power.

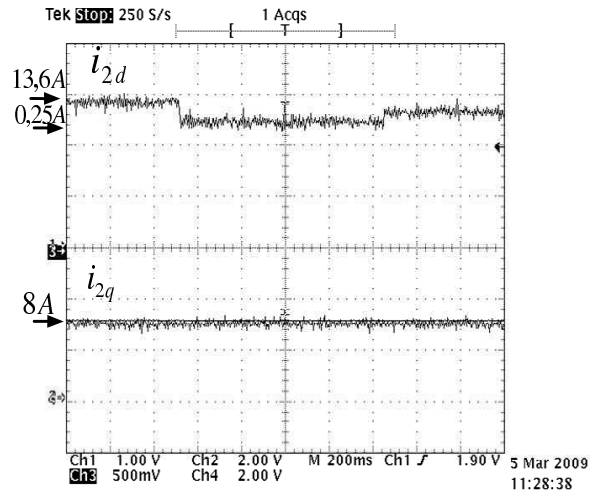


Fig. 11. Rotor currents of response of step test of reactive power.

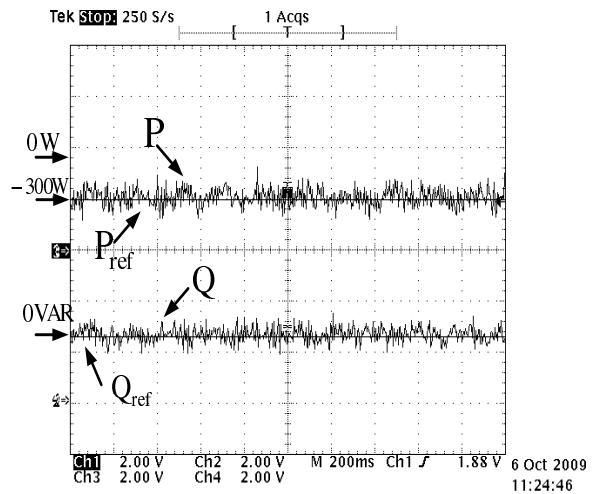


Fig. 12. Active and Reactive Power of DFIG.

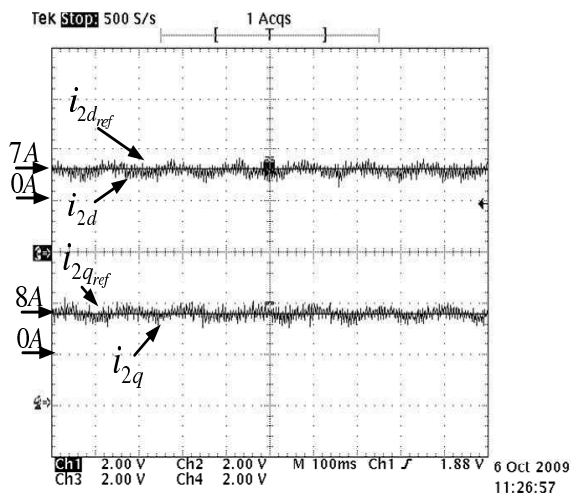


Fig. 13. Rotor current of DFIG.

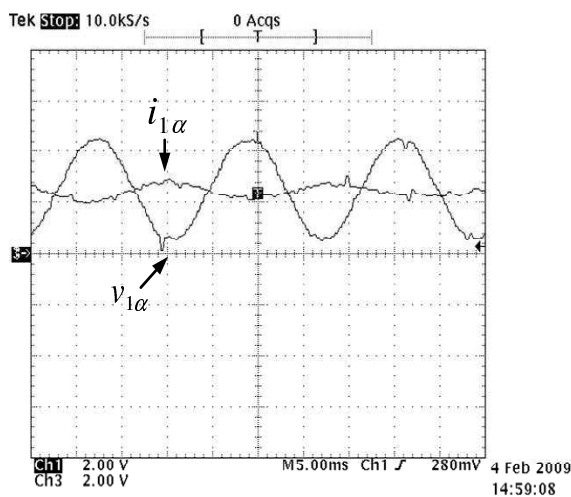


Fig. 14. Stator voltage (18 V/div.) and current (0.38 A/div.).

In the last test, the generator operates with several speed and a constant active and reactive power reference of 0W and 0VA, respectively. The rotor current reference are also calculated using Equations (22) and (23). In this case, this test just maintains the magnetization of the generator. The response of the active and reactive power is shown in Figure 15 and the rotor current is presented in Figure 16. The rotor speed in several operations and the rotor current of phase α is shown in Figure 17. The satisfactory performance of the controller is can be seen during several speed operation due fact the reference is followed and the DFIG operates from super-synchronous operation to sub-synchronous operation.

V. CONCLUSION

This paper has presented a deadbeat active and reactive power control for doubly fed induction generator. The controller uses the DFIG discretized dynamic equations to calculate the required rotor voltages in order to the active and the reactive power values reach the desired reference within a few sampling intervals due to the fact the controller

response depends of the order of the system and the sampling period. The deadbeat control uses a rotor current control for this objective. This strategy operates with constant switching frequency that overcomes the drawbacks of conventional DPC [28, 29]. Experimental tests with parameters variations have to be done to analyze the performance of the controller.

The experimental results confirm the effectiveness of the deadbeat power controller during several operating conditions.

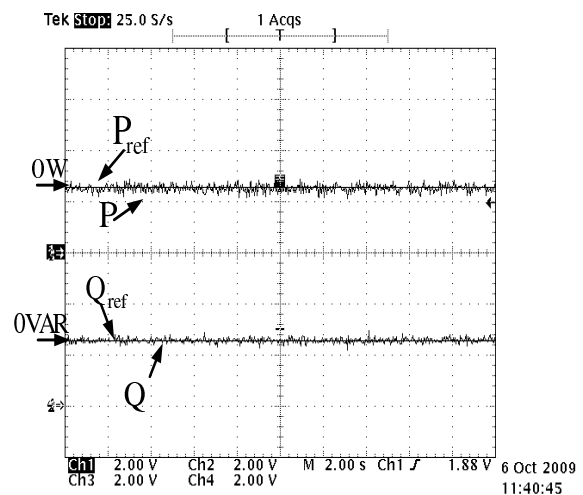


Fig. 15. Active and reactive power of DFIG.

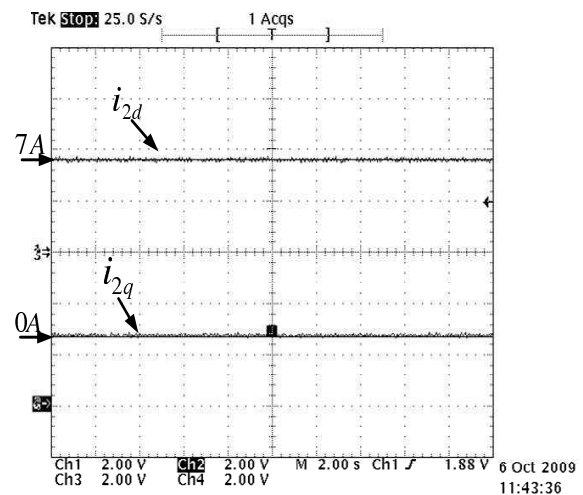


Fig. 16. Rotor current in steady state.

ACKNOWLEDGEMENT

The authors would like to thank to CAPES, FAPESP and CNPQ by the financial support and the Texas Instruments for the dsp donation.

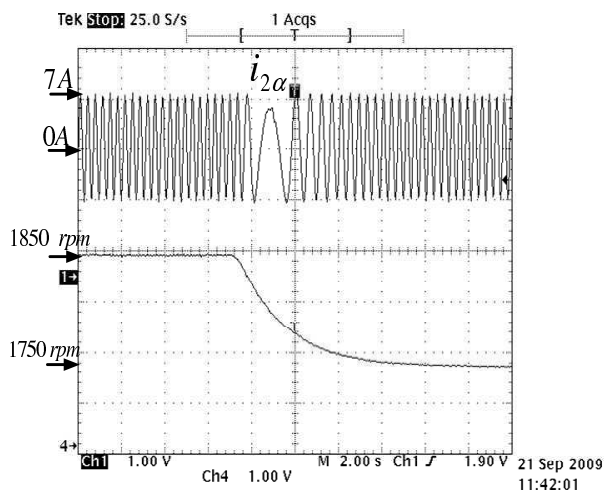


Fig. 17. Rotor current and speed of DFIG.

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APPENDIX

Doubly-fed induction generator parameters: $R_1 = 2.2 \Omega$; $R_2 = 1.764 \Omega$; $L_m = 0.0829 H$; $L_{l1} = 0.0074 H$; $L_{l2} = 0.0074 H$; $J = 0.05 Kg \cdot m^2$; $NP = 2$; $PN = 2.25 KW$; $V_N = 220 V$.

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