Decoupled Control of Doubly Fed Induction Machine Fed by SVM Matrix Converter

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Abstract – In this paper a decoupled control of a doubly-fed induction machine (DFIM) feed by a matrix converter is presented. It provides a robust regulation of the stator side active and reactive powers by the direct and quadratic components of the stator current vector, presented in a line-voltage-oriented reference frame. In this case, the stator windings are directly connected to the line grid, while the rotor windings are supplied by this later through a matrix converter controlled by a space vector modulation technique. The proposed solution is suitable for both energy generation and electrical drive applications with restricted speed variation range.

Keywords: DFIM, Decoupled control, Matrix converter, Space vector modulation, Robustness

1. Introduction

The doubly fed induction machine attractive alternative to cage rotor induction and synchronous machines in high power applications where the speed range is limited [1,2]. The typical connection scheme of a DFIM consists to connect the stator windings directly to the line grid, while the rotor windings are supplied by the line grid through an AC/AC converter (Fig.1).

Recently, significant research activity has been concentrated on the development of new control algorithms for a DFIM and new power converter technologies. Matrix converter (MC) introduced in [3,4], have been found as interesting alternative to standard AC/DC/AC converters.

The MC, as three-to-three phases direct converter, has number of attractive features such as: power converter adjustment capability and it does not involve a DC voltage link and the associated large capacitor,

This work was supported by the LEB-Research laboratory, Depatment of Electrical Engineering.and it allows bidirectional power flow. In the literature, two methods of control are adapted for the control of the matrix converter, such-that the Venturini and SVM methods, the main advantage of the SVM method lies in lower switching losses compared with the Venturini method [5, 6, 7], (appendix A).

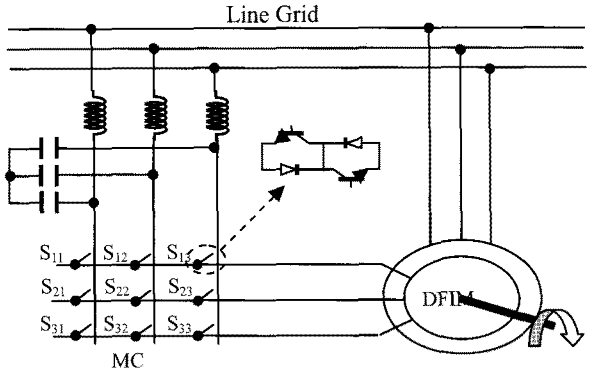

Fig. 1. Typical connection scheme of a DFIM

The fundamentals of DFIM vector control are presented in [8, 9, 10]. Different strategies were proposed to solve the DFIM decoupled control of active and reactive powers problem. In [1], an alternative approach for the design of DFIM active-reactive power control is proposed. The controller development is based on implementation of a line-voltage vector oriented reference frame. Since the line-voltage vector can easily be measured with negligible errors, this reference frame is DFIM parameter-independent in contrast to the field-orientation one.

In this paper a new application of the SVM matrix converter for active and reactive powers decoupled control by the direct and quadratic components of the stator current vector is developed. A line voltage-vector reference frame is adopted. In addition, the estimation of the stator voltages are required to determine the position of considered reference frame. Rotor speed and stator currents estimations are also used by the considerate control algorithm.

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The proposed solution of DFIM shows very good robustness with respect to variations of active and reactive powers references. Consequently to the power factor adjustable. This solution is suitable for all of the applications where limited speed variations around the synchronous speed are present. Since the power handled by the rotor side (slip power) is proportional to slip, an energy conversion is possible using a rotor-side power converter, which handles only a small fraction of the overall system power.

2. Dfim Model And Control Objectives

Assuming linear magnetic circuits, the dynamics of a balanced non-saturated DFIM in a rotating (d-q) reference frame attached to the stator voltage vector are given by:

$$\begin{cases} v_{sd} = R_s i_{sd} + \dfrac{d\psi_{sd}}{dt} - \omega_s \psi_{sq} \\ v_{sq} = R_s i_{sq} + \dfrac{d\psi_{sq}}{dt} + \omega_s \psi_{sd} \\ v_{rd} = R_r i_{rd} + \dfrac{d\psi_{rd}}{dt} - (\omega_s - \omega)\psi_{rq} \\ v_{rq} = R_r i_{rq} + \dfrac{d\psi_{rq}}{dt} + (\omega_s - \omega)_{rd} \\ \dot{\omega} = \dfrac{1}{J}[T_m - T_{em}] \\ T_{em} = \dfrac{3}{2} p \dfrac{L_m}{L_r} (\psi_{rd} i_{sq} - \psi_{rq} i_{sd}) \end{cases} \quad (1)$$

In which: i_{sd}, i_{sq}, i_{rd}, i_{rq}, ψ_{sd}, ψ_{sd}, ψ_{rd}, ψ_{rq}, v_{sd}, v_{sq}, v_{rd}, v_{rq} are the components of the spaces vectors of the stator and rotor currents, flux and voltages, and R_r, R_s, L_s, L_r are resistances and inductances of the stator and rotor windings, L_m is magnetizing inductance; ω - the rotor speed; T_m- the external torque applied to the DFIM; T_{em}- the electromagnetic torque produced by the machine; J the total rotor inertia and ω_s the speed of the (d-q) reference frame with respect to the a-axis of the fixed stator reference frame (α-β).

$$\begin{aligned} x_{sdq} &= e^{-j\theta_s} x_{s\alpha\beta} \\ x_{rdq} &= e^{-j(\theta_s - \theta)} x_{ruv} \end{aligned} \quad (2)$$

where

$$e^{-j\delta} = \begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix}, \; j = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \quad (3)$$

where: x_{yz} stands for two dimensional vectors in the generic (y-z) reference frame; subscript 's' stands for stator variables while 'r' for rotor variables; (u-v) indicates rotor reference frame and θ is the rotor angle.

The main control objective considered is the regulation of DFIM stator-side active and reactive powers, given by:

$$\begin{aligned} P_s &= \frac{3}{2}(v_{sd} i_{sd} + v_{sq} i_{sq}), \\ Q_s &= \frac{3}{2}(v_{sq} i_{sd} - v_{sd} i_{sq}) \end{aligned} \quad (4)$$

In order to reduce the effect of the above inaccuracies in the reference frame generation and in vector transformation, a line (stator) voltage vector reference frame (d-q) has been adopted (the d-axis is aligned with the line voltage vector). This reference frame is independent of machine parameters and position sensor resolution; only information from two voltage sensors and rotor position sensor are needed, instead of four current sensors.

The synchronous stator voltage oriented reference (the d-axis is aligned with the line voltage vector) frame is defined by v_{sd}=U and v_{sq}=0.

The expression of active and reactive powers (4) can be presented in the synchronous stator voltage oriented reference as:

$$P_s = \frac{3}{2} U i_{sd}, \; Q_s = -\frac{3}{2} U i_{sq} \quad (5)$$

From (5), it follows that active-reactive power control objective is equivalent to active-reactive stator currents control. Let us suppose P_s^* and Q_s^* are the references for the power components at stator side for the DFIM. The references for the components of the stator current, are given by

$$i_{sd}^* = \frac{2}{3}\frac{P_s^*}{U}, \; i_{sq}^* = -\frac{2}{3}\frac{Q_s^*}{U} \quad (6)$$

The control problem of DFIM is formulated in terms of stator direct and quadratic components current regulation as to consider the DFIM model (1) under coordinate transformation (2). Let assume that:

The stator voltage amplitude and frequency are constants (stator windings are directly connected to the line-grid).

Stator currents and voltages as well as rotor position and speed are available from estimations.

3. Design of A Decoupled Control Algorithm

The design procedure is performed in two steps: a flux control is designed first, to achieve flux regulation, and then the current control algorithm is developed [2].

Let define the flux regulation errors as:

$$e_{\psi_{rd}} = \psi_{rd} - \psi^*_{rd}\,, e_{\psi_{rq}} = \psi_{rq} - \psi^*_{rq} \tag{7}$$

Where flux references, ψ^*_{rd} and ψ^*_{rq}, will be defined later according to stator current control objectives.

The first order derivate of (7), gives

$$\dot e_{\psi rd} = \dot\psi_{rd} - \dot\psi^*_{rd}\,, \dot e_{\psi rq} = \dot\psi_{rq} - \dot\psi^*_{rq} \tag{8}$$

Using the mathematical model of DFIM (1), the system of equations (8) can be rewritten as:

$$\begin{aligned} \dot e_{\psi rd} &= -\frac{1}{T_r}(e_{\psi rd} + \psi^*_{rd}) + \omega_r(e_{\psi rq} + \psi^*_{rq}) + \\ &+ \frac{1}{T_r} M_{sr}(e_{isd} + i^*_{sd}) + v_{rd} - \dot\psi^*_{rd} \\ \dot e_{\psi rq} &= -\frac{1}{T_r}(e_{\psi rq} + \psi^*_{rq}) - \omega_r(e_{\psi rd} + \psi^*_{rd}) + \\ &+ \frac{1}{T_r} M_{sr}(e_{isq} + i^*_{sq}) + v_{rq} - \dot\psi^*_{rq} \end{aligned} \tag{9}$$

where $\omega_r = \omega_s - \omega$ is the slip angular pulsation.

Constructing the flux control algorithm as

$$\begin{aligned} v_{rd} &= \frac{1}{T_r}\psi^*_{rd} - \omega_r\psi^*_{rq} - \frac{1}{T_r}L_m i^*_{sd} + \dot\psi^*_{rd} + u_d \\ v_{rq} &= -\frac{1}{T_r}\psi^*_{rq} + \omega_r\psi^*_{rd} - \frac{1}{T_r}L_m i^*_{sq} + \dot\psi^*_{rq} + u_q \end{aligned} \tag{10}$$

The flux error dynamics becomes

$$\begin{aligned} \dot e_{\psi rd} &= -\frac{1}{T_r}e_{\psi rd} + \omega_r e_{\psi rq} + \frac{1}{T_r}L_m e_{isd} + u_d \\ \dot e_{\psi rq} &= -\frac{1}{T_r}e_{\psi rq} - \omega_r e_{\psi rd} + \frac{1}{T_r}L_m e_{isq} + u_q \end{aligned} \tag{11}$$

where u_d, u_q will be defined later.

Applying the control algorithm (10) and from mathematical model (1), the current error can be rewritten as

$$\begin{aligned} \dot e_{isd} &= -\beta e_{isd} + \omega_s e_{isq} + \frac{\alpha}{T_r} e_{\psi rd} + \alpha\omega e_{\psi rq} - \alpha u_d - \\ &- \dot i^*_{sd} - \alpha\dot\psi^*_{rd} - \frac{R_s}{\sigma} i^*_{sd} + \omega_s i^*_{sq} + \frac{1}{\sigma}U + \alpha\omega_s\psi^*_{rq} \\ \dot e_{isq} &= -\beta e_{isq} - \omega_s e_{isd} + \frac{\alpha}{T_r} e_{\psi rq} - \alpha\omega e_{\psi rd} - \alpha u_q - \\ &- \dot i^*_{sq} - \alpha\dot\psi^*_{rq} - \frac{R_s}{\sigma} i^*_{sq} - \omega_s i^*_{sd} - \alpha\omega_s\psi^*_{rd} \end{aligned} \tag{12}$$

where

$$T_r = \frac{L_r}{R_r}, \sigma = L_s\left(1 - \frac{L_m^2}{L_s L_r}\right), \alpha = \frac{L_m}{\sigma L_r}, \beta = \left(\frac{R_s}{\sigma} + \frac{\alpha L_m}{T_r}\right)$$

From equations (12) it follows that flux references should satisfy the following differential equations

$$\begin{aligned} \dot\psi^*_{rd} &= \frac{1}{\alpha}\left(\alpha\omega_s\psi^*_{rq} + \frac{1}{\sigma}U - \frac{R_s}{\sigma}i^*_{sd} + \omega_s i^*_{sq} - \dot i^*_{sd}\right) \\ \dot\psi^*_{rq} &= \frac{1}{\alpha}\left(-\alpha\omega_s\psi^*_{rd} - \frac{R_s}{\sigma}i^*_{sq} - \omega_s i^*_{sd} - \dot i^*_{sq}\right) \end{aligned} \tag{13}$$

Substituting (13) into (12) the resulting current-flux error dynamics becomes

$$\begin{aligned} \dot e_{i_{sd}} &= -\beta e_{i_{sd}} + \omega_s e_{i_{sq}} + \frac{\alpha}{T_r} e_{\psi_{rd}} + \alpha\omega e_{\psi_{rq}} - \alpha u_d \\ \dot e_{i_{sq}} &= -\beta e_{i_{sq}} - \omega_s e_{i_{sd}} + \frac{\alpha}{T_r} e_{\psi_{rq}} - \alpha\omega e_{\psi_{rd}} - \alpha u_q \end{aligned} \tag{14}$$

A particular solution of (13), where oscillating terms are avoided, is given by

$$\begin{aligned} \begin{bmatrix} \psi^*_{rd} \\ \psi^*_{rq} \end{bmatrix} = \frac{1}{\sigma\alpha}\Bigg\{ & \frac{1}{\omega_s}J\begin{bmatrix} U \\ 0 \end{bmatrix} + \left(\sigma I - \frac{R_s}{\omega_s}J\right)\begin{bmatrix} i^*_{sd} \\ i^*_{sq} \end{bmatrix} \\ & - R_s\sum_{k=1}^{\infty}\left[\left(\frac{1}{\omega_s}J\right)^{k+1}\frac{d^k}{dt^k}\begin{bmatrix} i^*_{sd} \\ i^*_{sq} \end{bmatrix}\right]\Bigg\} \end{aligned} \tag{15}$$

From (15) it follows that for arbitrary trajectories of current reference all of the time derivatives together with their initial conditions should be known. The following developments is based on the assumption that both current reference signals have bounded first time-derivate with all of the higher order ones equal to zero. Then the flux references are

$$\psi_{rd}^{*}=\frac{1}{\alpha\omega_s}\left(\frac{Rs}{\sigma}i_{sd}^{*}-\omega_s i_{sq}^{*}-\frac{1}{\sigma}U-\frac{1}{\sigma\omega_s}\dot{i}_{sq}^{*}\right)$$
$$\psi_{rq}^{*}=\frac{1}{\alpha\omega_s}\left(-\frac{Rs}{\sigma}i_{sq}^{*}-\omega_s i_{sd}^{*}-\frac{1}{\sigma\omega_s}\dot{i}_{sd}^{*}\right) \tag{16}$$

with $\dot{i}_{sd}^{*}=\dot{i}_{sq}^{*}=0$.

In order to compensate, during steady-state conditions, for constant perturbation generated by DFIM parameter variations and error in rotor position measurement, the following two-dimensional proportional-integral current controller is designed

$$u_d=\frac{1}{\alpha}\left(k_p e_{i_{sd}}+\lambda e_{i_{sq}}-y_d\right),\ \dot{y}_d=-k_i e_{i_{sd}}-\lambda\frac{R_s}{\sigma}e_{i_{sq}}$$
$$u_q=\frac{1}{\alpha}\left(k_p e_{i_{sq}}-\lambda e_{i_{sd}}-y_q\right),\ \dot{y}_q=-k_i e_{i_{sq}}+\lambda\frac{R_s}{\sigma}e_{i_{sd}} \tag{17}$$

where $k_p>0$ and $k_i>0$ are the proportional and integral gains of the current controllers and $\lambda = k_i\omega_s^{-1}$.

4. Space Vector Modulation Control of the Matrix Converter

The space vector modulation (SVM) represents the three-phase input currents and output line-to-line voltages as space vectors. It is based on the concept of approximating a rotating reference voltage vector with those voltages physically realisable on a matrix converter. For nine bidirectional switches, there are 27 possible switching configurations available in which only 21 are commonly utilized to generate the desired space vectors in the SVM control method. These 21 configurations in which may be divided into four groups [3, 6, 7]

The first three groups (±1, ±2, ±3, ±4, ±5, ±6, ±7, ±8, ±9) have two common features; namely, each of them consists of six vectors holding constant angular positions and each of them formulates a six-sextant hexagon as shown in Fig. 2,

The second group comprising three zero vectors is also used in this method. The modulation process consists of two procedures; vector selection and vector on-time duration calculation.

At a given time instant T_s, the SVM method selects four stationary vectors to approximate a desired reference voltage with the constraint of input power factor. To achieve this, the amplitude and phase angle of the reference rotor voltage vector are calculated and the desired phase angle of the input current vector is determined in advance.

The general formulae to calculate the on-time durations, have been given as [6]

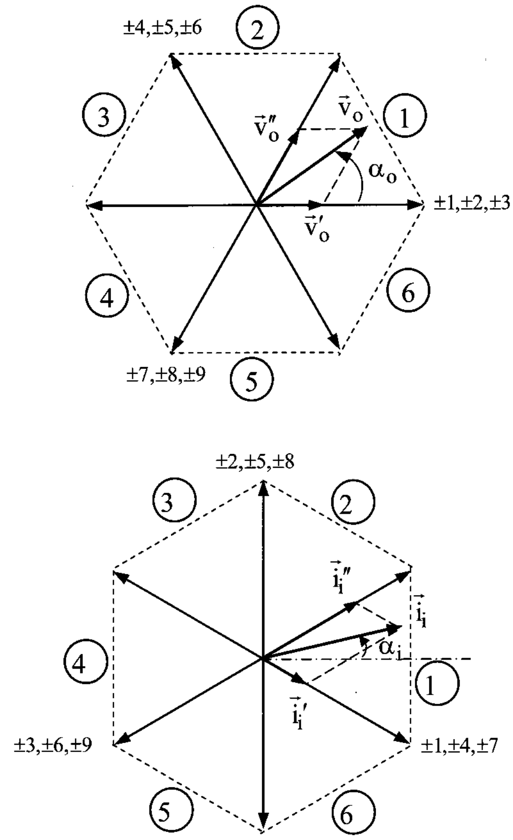

Fig. 2. Output voltage and input current space vectors

$$\delta_1=\frac{2}{\sqrt{3}}q\sin\left[\alpha_o-(k_v-1)\frac{\pi}{3}\right]\sin\left[\frac{\pi}{6}-\left(\alpha_i-(k_i-1)\frac{\pi}{3}\right)\right] \tag{18}$$

$$\delta_2=\frac{2}{\sqrt{3}}q\sin\left[\alpha_o-(k_v-1)\frac{\pi}{3}\right]\sin\left[\frac{\pi}{6}+\left(\alpha_i-(k_i-1)\frac{\pi}{3}\right)\right] \tag{19}$$

$$\delta_3=\frac{2}{\sqrt{3}}q\sin\left[k_v\frac{\pi}{3}-\alpha_o\right]\sin\left[\frac{\pi}{6}-\left(\alpha_i-(k_i-1)\frac{\pi}{3}\right)\right] \tag{20}$$

$$\delta_4=\frac{2}{\sqrt{3}}q\sin\left[k_v\frac{\pi}{3}-\alpha_o\right]\sin\left[\frac{\pi}{6}+\left(\alpha_i-(k_i-1)\frac{\pi}{3}\right)\right] \tag{21}$$

$$\delta_0=1-(\delta_1+\delta_2+\delta_3+\delta_4) \tag{22}$$

Where $q=V_O/V_i$ is the voltage transfer ratio, α_o and α_i

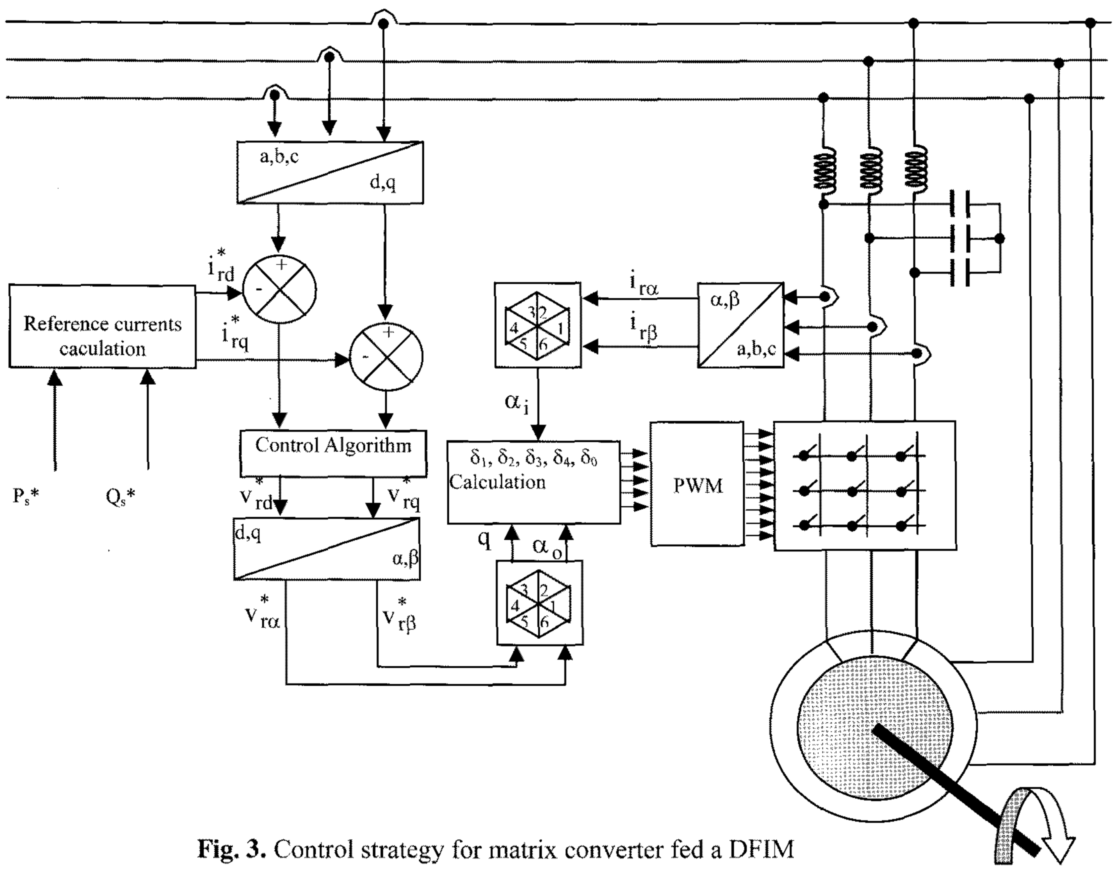

Fig. 3. Control strategy for matrix converter fed a DFIM

are the phase angles of the output voltage and input current vectors, respectively, and k_v, k_i are the output voltage sector and input current vector sector.

5. Diagram of The Control Process

In this section, the decoupled control of active and reactive power control by the direct and quadratic components of stator currents of the DFIM fed through a matrix converter is synthesized by the synoptic diagram as shown in figure 3.

To guarantee stable operation and to enable independent control active and reactive powers of the DFIM, a model based PI controllers is developed using the mathematical model equations (1).

The desired P_S^* and Q_S^* can determine the reference stator currents, which allows the calculation of the rotor voltage reference components in which they are used with a estimate rotor currents for calculates switching duration of space vectors, and outputs them as PWM signals to matrix converter. The latter is modelled using ideal switches.

To guarantee a drive of the DFIM around its speed of synchronism, a PI controller is used.

6. Simulation Results

In order to verify the robustness of the proposed control strategy of the generation system, the numerical simulations have been carried out using MATLAB. The simulation tests have been performed using a small (5 kW) doubly fed induction machine, whose rated data are reported in Appendix B.

The direct and quadratic components of the stator current and its reference are reported in figures 4 and 5. These figures show good pursuit, except that the presence of the oscillations during the transient mode caused by time of start up of primary mover. A very good decoupling is obtained between the direct and quadratic components of the stator current. Consequently between the active and reactive powers (Figure.6), this leads to a good control of the power flow between the grid and the machine at all time.

In figure 6, the DFIM delivers the active and reactive powers with power factor equal to 0.6 and 0.8 towards the grid during the period (1.9-3.75 s). At the period (3.75-4.8 s) the DFIM functions with a unit power factor. During the period (4.8-7), the DFIM absorbs the reactive power.

Figure 7 shows the active and reactive power delivered at the rotor through the matrix converter with different power factor.

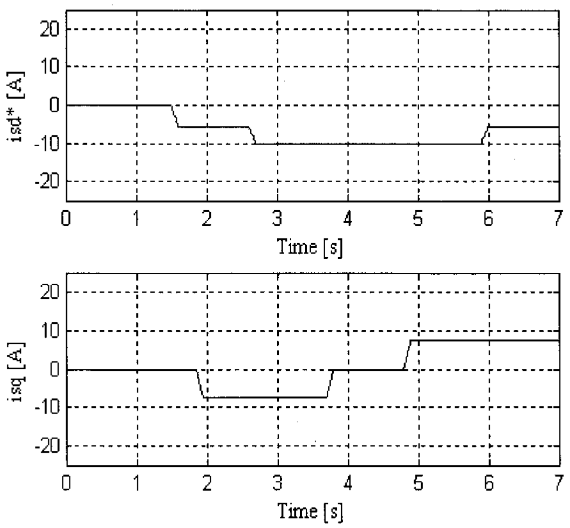

Fig. 4. Components of stator reference current

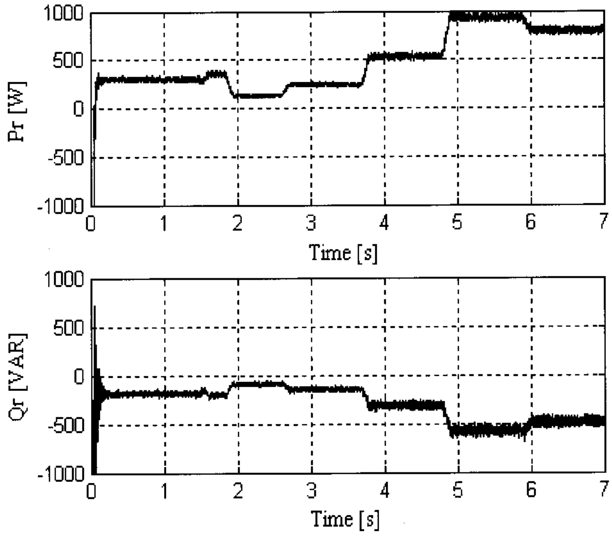

Fig. 7. Rotor active and reactive powers

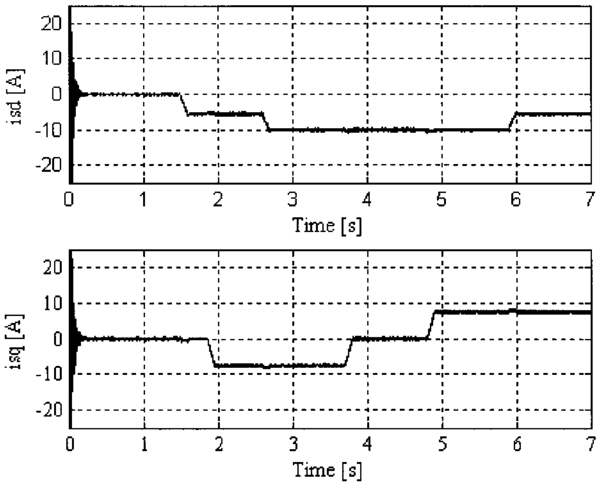

Fig. 5. Components of stator current

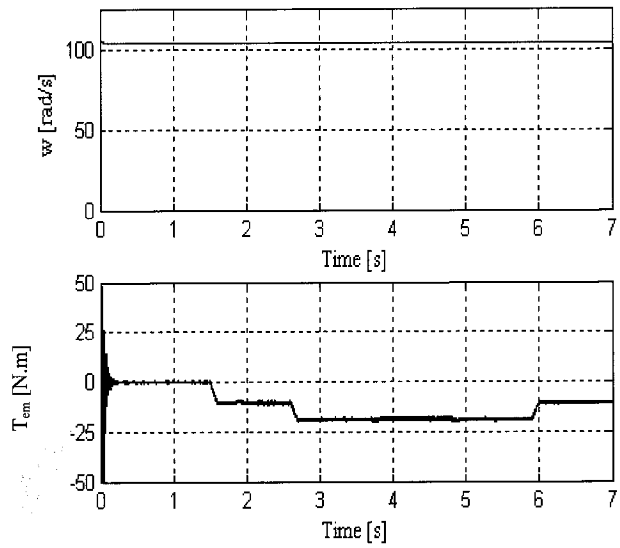

Fig. 8. Speed and Torque of DFIM

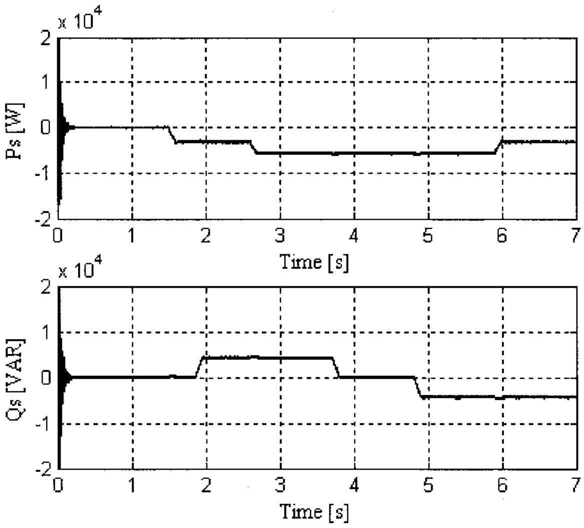

Fig. 6. Stator active and reactive powers

The speed and torque of the DFIM are reported in figure 8. According to the latter, that motoring speed stays constant because the regulation speed of the primary mover in order to guaranteed the tracking of the DFIM in its synchronous speed. In addition, the torque depends directly on the direct component of the stator current, consequently to the active power.

The phase rotor voltage and current are obtained at the output side of SVM matrix converter, are represented by figure 9. The use of SVM matrix converter makes it possible to improve the sinusoidal waveform of the stator current, as illustrated by the figure 10. Consequently a clear energy injected to the grid is obtained.

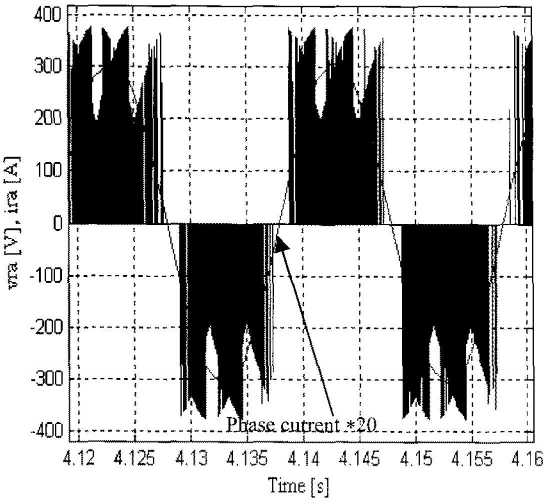

Fig. 9. Phase rotor voltage and current

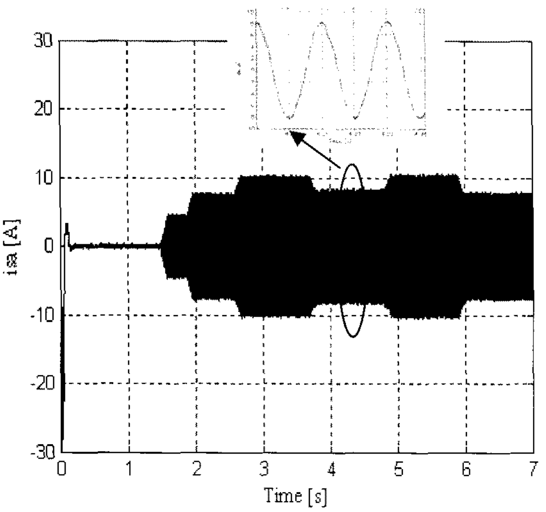

Fig. 10. Phase stator current

7. Conclusion

The control of active and reactive powers flow between the DFIM and grid by the stator current provides global asymptotic regulation in presence of the stator current reference variation. The simulation tests confirm the high dynamic performance and the decoupled active and reactive powers control by adjusting stator currents and power factor are obtained by proposed controller. The proposed solution is suitable for energy generation applications in particularly for wind energy generation system and variable speed drives, where restricted variations of the speed around the synchronous velocity are present. The use of the SVM technique for matrix converter control, allows it possible to obtain perfectly sinusoidal currents on the level of the stator, therefore the energy provided by the machine to the grid is a clean energy without harmonics.

APPENDIX A

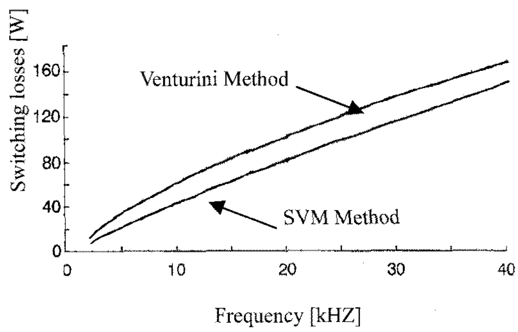

Fig. 11. Switching losses as a function of switching frequency

The simulated converter losses for the two control methods are plotted as function of switching frequency in fig.11, [3].

Appendix B

The nominal parameters of the DFIM adopted are: P_n=5 W, 380 (Y), 50 Hz, 100 rad/s, 50 N.m, R_s=0.95 Ω, R_r=1.8 Ω, L_s=0.094 H, L_r=0.088 H, L_m=0.082 H.

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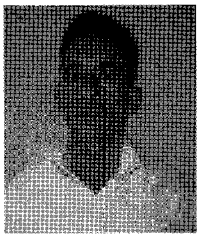

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