MATRIX CONVERTER FOR SIX PHASE INDUCTION MACHINE DRIVE SYSTEM

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ABSTRACT

In this paper, a novel vector controlled six- phase induction machine which is fed from six-phase matrix converter is proposed. Though the practical implementation of matrix converter to vector controlled three phase induction motors is limited and still under investigation due to switches devices implementation difficulties and complication of modulation technique and commutation control, but all research works published so far agreed that the performances of three phase induction motors supplied from matrix converters are superior to that obtained using conventional pulse width modulation controlled inverter.

Owing to that, we propose in the present work via simulation the application of six phase matrix converter for the supply of vector controlled six phase induction machines.

The paper discusses all components used in the simulation, namely the vector control law, six phase matrix converter as well as the mathematical model of a six phase induction machine with electrical angle between any two three phase stator winding equal to 60 electrical degrees. A scalar modulation scheme with three intervals which ensures high performance and meets desired requirements is used for the control of matrix converter.

Simulation results obtained are very satisfactory and demonstrate the possibility of using vector control of six-phase induction machine fed from a six- phase matrix converter. We believe that simulation results obtained will be of great benefit for the future practical investigations.

Keywords: *Six-phase Matrix Converter, vector control, six-phase induction machine.*

1. INTRODUCTION

Matrix converter fed motor drive is superior to pulse width modulation (PWM) inverter drives because it provides bidirectional power flow, sinusoidal input/output currents, and adjustable input power factor. Furthermore, matrix converter allows a compact design due to the lack of dc-link capacitors for energy storage. However, only a few of practical matrix converters have been applied to vector control system of induction motors for some well-know reasons [1]:

1) Implementation of switch devices in matrix converter is difficult;

2) Modulation technique and commutation control are more complicated than conventional PWM inverter.

Six-phase ac motor drives are often considered as a viable solution when reduction of the converter per-phase rating is required due to the high motor power. The standard choice is a six-phase induction machine with two three-phase windings on stator [2]. The special displacement between the two three-phase windings is 60° and neutral points of two windings are normally isolated. If the neutral points of the two three-phase windings are isolated, torque is produced by the fundamental stator current harmonic only. If the neutral points are connected, torque production can be enhanced by the third harmonic stator current injection.

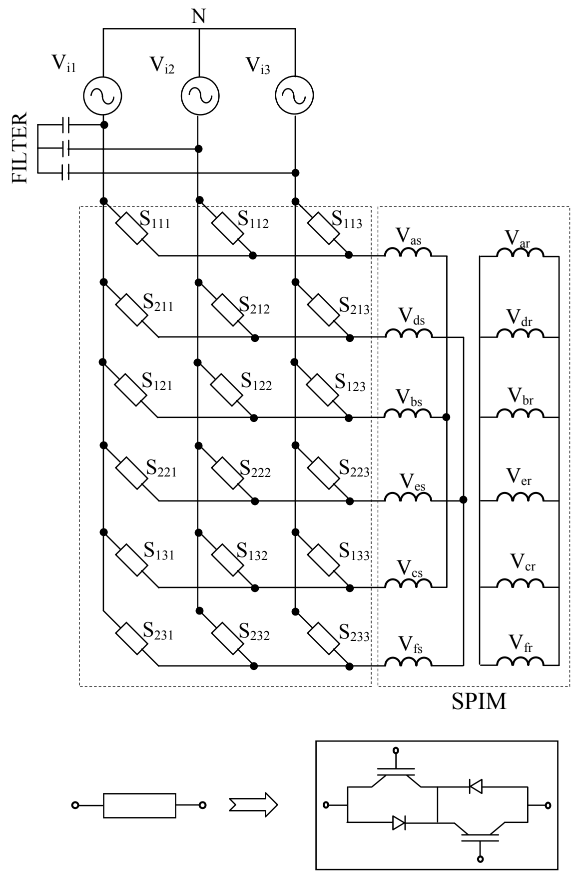


Fig. 1 Circuit diagram of six-phase matrix converter fed six phase induction machine (SPIM).

2. VECTOR CONTROL OF SPIM

Vector control, published for the first time by Blaschke in his pioneering work in 1972, consists in adjusting the flux by a component of the current and the torque by the other component. For this purpose, it is necessary to choose a d-q reference frame rotating synchronously with the rotor flux space vector, in order to achieve decoupling control between the flux and the produced torque. This technique allows to obtain a dynamical model similar to the DC machine [3,4].
Rotational transformation, leading to the d-q subsystem of the equations, is applied in conjunction with rotor equations (Fig.2). The matrix has for the six-phase machine the following form:

$$[D_r] = \begin{bmatrix} \cos(\theta_r) & -\sin(\theta_r) & \\ \sin(\theta_r) & \cos(\theta_r) & \\ & & [I]_{4\times 4} \end{bmatrix} \tag{1}$$

where [I] is the diagonal 4×4 unity matrix.
Upon application of the rotational transformation the equations for stator and rotor, respectively, become [4]:

$$\begin{cases} \dfrac{di_{sd}}{dt} = \dfrac{-1}{\sigma\tau_s^{'}} i_{sd} + \omega_s i_{sq} + \dfrac{\mu}{\sigma\tau_r}\phi_{rd} + \dfrac{\mu}{\sigma}\omega_r\phi_{rq} + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{sq}}{dt} = \dfrac{-1}{\sigma\tau_s^{'}} i_{sq} - \omega_s i_{sd} + \dfrac{\mu}{\sigma\tau_r}\phi_{rq} - \dfrac{\mu}{\sigma}\omega_r\phi_{rd} + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d\phi_{rd}}{dt} = \dfrac{-1}{\tau_r}\phi_{rd} + \dfrac{M}{\tau_r} i_{sd} + (\omega_s - \omega_r)\phi_{rq} \\ \dfrac{d\phi_{rq}}{dt} = \dfrac{-1}{\tau_r}\phi_{rq} + \dfrac{M}{\tau_r} i_{sq} - (\omega_s - \omega_r)\phi_{rd} \end{cases} \tag{2}$$

where

$$\sigma = 1 - \frac{M^2}{L_s L_r}, \quad \mu = \frac{M}{L_s L_r}, \quad \tau_s^{'} = \frac{L_s}{R_{seq}}$$

$$\tau_r = \frac{L_r}{R_r}, \quad R_{seq} = R_s + \frac{M^2}{L_r^2} R_r$$

and v_{sd}, v_{sq}, i_{sd} and i_{sq} are d-q components of stator voltage and current vectors respectively; Φ_{rd} and Φ_{rq} are the rotor flux d-q components and ω_r is the rotor electrical angular speed.

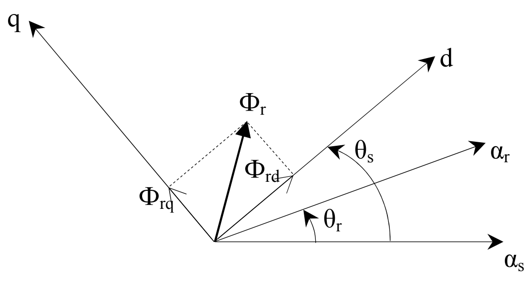


Fig. 2 d—q and α—β frames.

While the torque equation takes the form

$$T_e = P\frac{M}{L_r}(\phi_{rd} i_{sq} - \phi_{rq} i_{sd}) \tag{3}$$

and the mechanical equation is the following:

$$\frac{d\omega_r}{dt} = \frac{P}{J}(T_e - T_l) \tag{4}$$

in which J is the inertia coefficient, P is the number of poles and T_l is external load torque.
According to the model (2) – (4), if Φ_{rq} tends to zero, the rotor flux becomes independent from i_{sq} while the motor torque will be proportional to i_{sq}. It is the objective of the vector control. The only degree of freedom is the angular speed of d-q frame ω_s which must be used to regular Φ_{rq} to zero. According to (2), the stator voltage angular frequency ω_s is determined by the following vector control law:

$$\omega_s = \omega_r + \frac{M}{\tau_r}\cdot\frac{i_{sq}}{\phi_{rd}} \tag{5}$$

It can be easily shown that this vector control law guarantees the regulation of Φ_{rq} to zero if the motor parameters are well known. Nevertheless, the rotor time constant τ_r is a highly time variable parameter and its initial value knowledge is not enough to ensure an efficient control.
Replacing (5) to (2), we can write the following equations that describe the dynamic behaviour of vector controlled machine in d—q frame:

$$\begin{cases} \dfrac{di_{sd}}{dt} = \dfrac{-1}{\sigma\tau_s^{'}} i_{sd} + \omega_s i_{sq} + \dfrac{\mu}{\sigma\tau_r}\phi_r + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{d\phi_r}{dt} = \dfrac{-1}{\tau_r}\phi_r + \dfrac{M}{\tau_r} i_{sd} \\ \dfrac{di_{sq}}{dt} = \dfrac{-1}{\sigma\tau_s^{'}} i_{sq} - \omega_s i_{sd} - \dfrac{\mu}{\sigma}\omega_r\phi_r + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d\omega_r}{dt} = \dfrac{P^2 M}{jL_r}\phi_r i_{sq} - \dfrac{P}{j} T_l \end{cases} \tag{6}$$

where $\phi_r = \dfrac{M}{L_r}\sqrt{\phi_{rd}^2 + \phi_{rq}^2}$

As can be seen from equation (6), the rotor flux is independent to the load torque and to i_{sq} if Φ_{rq} is well regulated to zero. The rotor electrical speed angular is dependent to the load torque, rotor flux and current i_{sq}.

3. MATRIX CONVERTER THEORY

The schematic diagram of a six-phase matrix converter is presented in fig. 1. Its inputs are the phase voltages v_{in1}, v_{in2}, v_{in3}, and its outputs are the voltages v_{as}, v_{bs}, v_{cs}, v_{ds}, v_{es} and v_{fs}. The matrix converter components

($S_{111}, S_{112}, \ldots S_{233}$) represent eighteen bi-directional switches witch are capable to blocking voltage in both directions and to switching without any delays.
The matrix converter connects the three given inputs, with constant amplitude V_{in} and frequency $f_{in}=\omega_{in}/2\pi$, through the eighteen switches to the output terminals in accordance with calculated switching angles. The six-phase output voltages obtained have controllable amplitudes V_{ou} and frequency $f_{ou}= \omega_{ou}/2\pi$ [5, 6] .
The input three-phase voltages of the converter are given by:

$$\begin{bmatrix} v_{in1} \\ v_{in2} \\ v_{in3} \end{bmatrix} = V_{in} \begin{bmatrix} \cos(w_{in}t) \\ \cos(w_{in}t - 2\pi/3) \\ \cos(w_{in}t - 4\pi/3) \end{bmatrix} \tag{7}$$

The required first harmonic of the output phase voltages of the unloaded matrix converter is:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ v_{ds} \\ v_{es} \\ v_{fs} \end{bmatrix} = V_{ou} \begin{bmatrix} \cos(\omega_{ou}t) \\ \cos(\omega_{ou}t - 2\pi/3) \\ \cos(\omega_{ou}t - 4\pi/3) \\ \cos(\omega_{ou}t - \alpha) \\ \cos(\omega_{ou}t - \alpha - 2\pi/3) \\ \cos(\omega_{ou}t - \alpha - 4\pi/3) \end{bmatrix} \tag{8}$$

The problem at hand may be defined as follows: with input voltages as equation (7), the matrix converter switching angles equations will be formulated so that the first harmonic of the output voltages will be as equation (8).
During the k^{th} switching cycle T_s ($T_s=1/f_s$), the first phase output voltage is given by [7]:

$$v_{as} = \begin{cases} v_{in1} & 0 \le t-(k-1)T_s < m_{111}^k T_s \\ v_{in2} & m_{111}^k T_s \le t-(k-1)T_s < (m_{111}^k + m_{112}^k)T_s \\ v_{in3} & (m_{111}^k + m_{112}^k)T_s \le t-(k-1)Ts < T_s \end{cases} \tag{9}$$

Where 'm's are defined by:

$$m_{ijl}^k = \frac{t_{ijl}^k}{T_s} \tag{10}$$

Where t^k_{ijl} is the time interval when S_{ijl} is in 'ON' state, during the k^{th} cycle, and k is being the switching cycle sequence number.
The 'm's have the physical meaning of duty cycle.

$$\sum_{i=1}^{2} m_{ijl}^k = m_{i11}^k + m_{i12}^k + m_{i13}^k = 1 \qquad \textit{and} \quad 0 < m_{ijl}^k < 1 \tag{11}$$

During any cycle T_s, the averaged value of the output voltage v_{as} is based on equation (9) and it's given by:

$$V_{as\_av}^{(k)} = v_{in1}^{(k)} m_{111}^{(k)} + v_{in2}^{(k)} m_{112}^{(k)} + v_{in3}^{(k)} m_{113}^{(k)} \tag{12}$$

Where $v_{in1}^{(k)}, v_{in2}^{(k)}$ *and* $v_{in3}^{(k)}$ are input voltages quasiconstant) during the k^{th} interval.
As can be seen, during the k^{th} interval, the averaged voltage is constant. It is worth noting that the function is a quantised variable function. The averaged value depends on the input voltages, which are time dependent.
Our aim is calculation of the 'm' values, which assures that the first harmonic of the output voltage matches the expression given in equation (8). In the time domain, the matrix converter's instantaneous output voltages are highly chopped, non sinusoidal functions.
With equation (12) valid for every t, the first harmonic of the output phase is given by [8,9]:

$$V_{ou}\cos(\omega_{ou}t) = m_{111}^{(k)} V_{in}\cos(\omega_{in}t) + m_{112}^{(k)}\cos(\omega_{in}t - \frac{2\pi}{3}) + m_{113}^{(k)}\cos(\omega_{in}t - \frac{4\pi}{3}) \tag{13}$$

in a similar manner, additional equations for v_{bs}, v_{cs}, v_{ds}, v_{es} and v_{fs} may be formulated. Therefore, for a six phase matrix converter, the problem of calculating the 'm' values is given by [9]:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ v_{ds} \\ v_{es} \\ v_{fs} \end{bmatrix} = \begin{bmatrix} m_{111} & m_{112} & m_{113} \\ m_{121} & m_{122} & m_{123} \\ m_{131} & m_{132} & m_{133} \\ m_{211} & m_{212} & m_{213} \\ m_{221} & m_{222} & m_{223} \\ m_{231} & m_{232} & m_{233} \end{bmatrix} \begin{bmatrix} v_{in1} \\ v_{in2} \\ v_{in3} \end{bmatrix} \tag{14}$$

4. SIMULATION RESULT

In order to verify the efficiency of the proposed drive scheme, we have developed a program in MATLAB/SIMULINK The system parameters are given in Appendix.

The calculated m-values are shown in Fig.3 at f_s=2 Khz, as can be seen, the m-values provide high quality switching patterns.

The average output voltages are depicted on Figs.4a-4d, one notices that the output voltages are limited to half for q=0.57. With an aim of improving q with 0.866, one ad to the output voltage the 3^{rd} harmonic of the input voltage with amplitude equal to $V_{im}/4$ and one subtracts the 3^{rd} harmonic from the output voltage with amplitude equal to $V_{om}/6$.

Figs.5a-5b shows the output voltages with their FFT. The main harmonic is located at 1 Khz and additional harmonics are around the switching frequency. The main harmonic is located at 2 Khz for the Figs.6a-6b. The output current presented in Fig.7 have very low harmonic content.

Simulation results of the starting process of the SPIM fed from a six-phase matrix converter at a frequency f_s=2 kHz are shown on the Fig.8. Simulation results of the direct vector control of the SPIM are given by the Fig.9. As can be seen, the decoupling carried out between the flux and the electromagnetic torque.

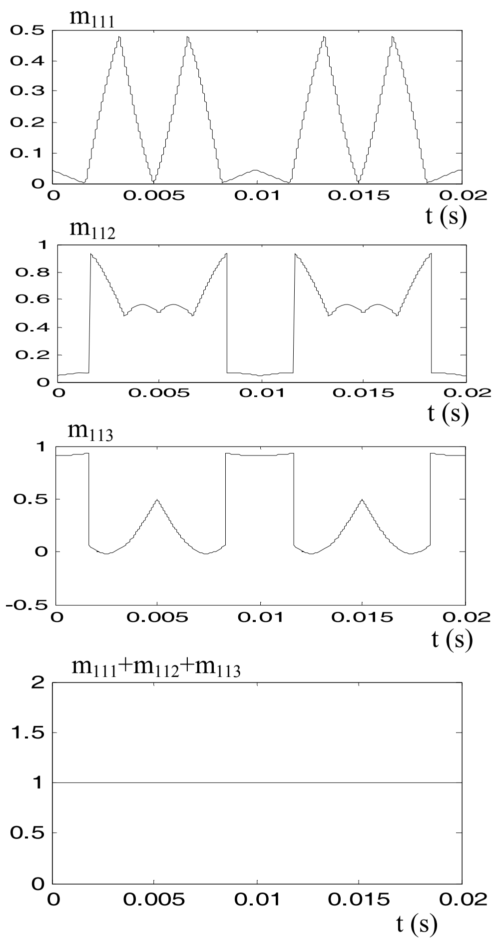


Fig. 3 Calculated values m_{ijl} , at:
f_s=2 Khz , q=0.866

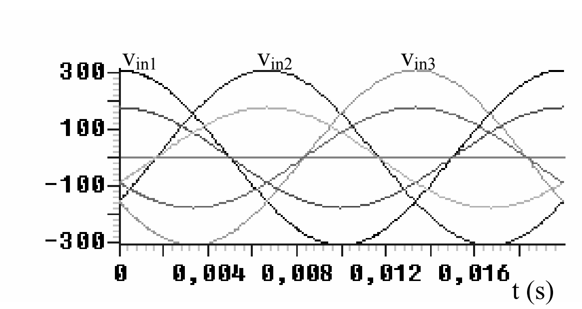


Fig. 4a Input and desired output voltages
v_{as}^* ,v_{bs}^* and v_{cs}^* for :
f_s=1 KHz, q=0.57

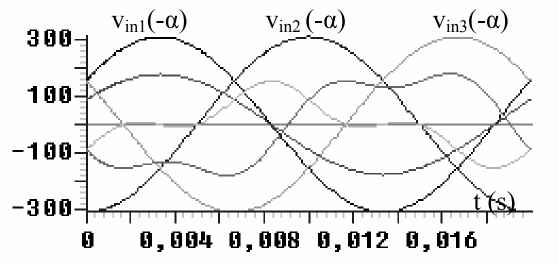


Fig. 4b Input and desired output voltages
v_{ds}^* ,v_{es}^* and v_{fs}^* for :
f_s=1 KHz, q=0.57

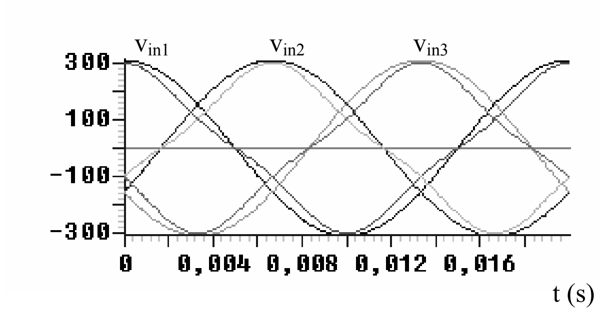


Fig. 4c Input and desired output voltages
v_{as}^* ,v_{bs}^* and v_{cs}^* for :
f_s=1 KHz, q=0.866

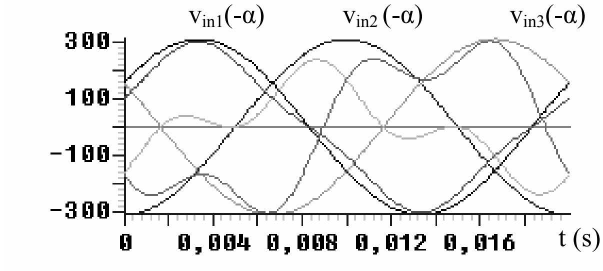


Fig. 4d Input and desired output voltages
v_{ds}^* ,v_{es}^* and v_{fs}^* for :
f_s=1 KHz, q=0.866

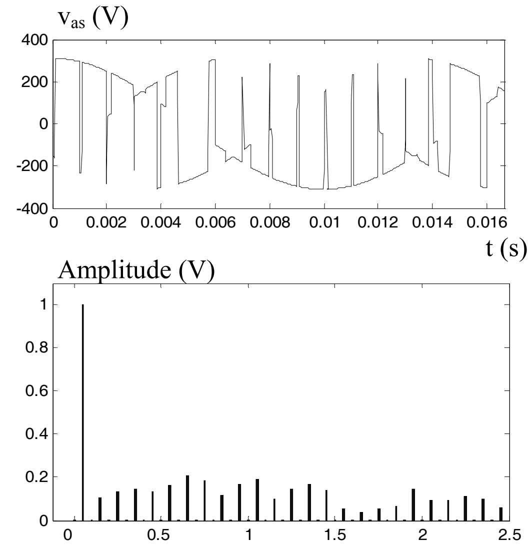


Fig. 5a v_{as} with FFT at f_s=1 Khz

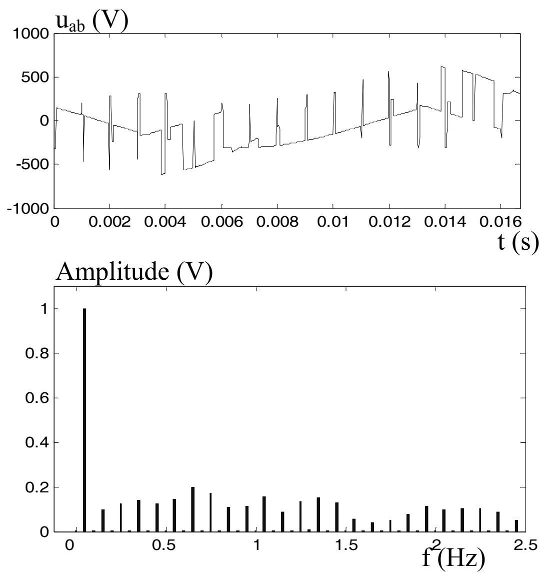


Fig. 5b u_{ab} with FFT at f_s=1 Khz

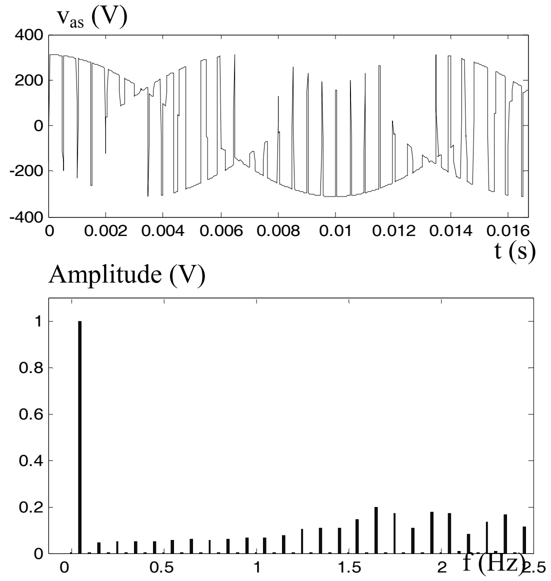


Fig. 6a v_{as} with FFT at f_s=2 Khz

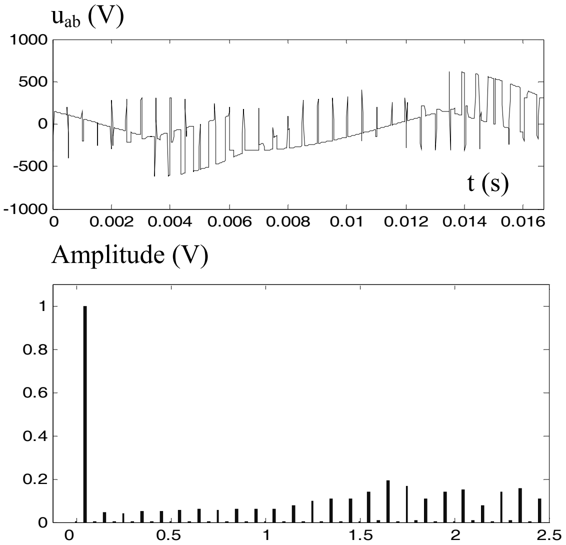


Fig. 6b u_{ab} with FFT at f_s=2 Khz

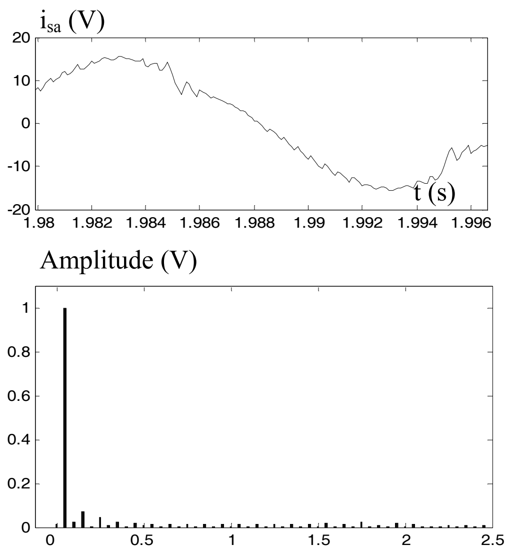


Fig. 7 i_{sa} with FFT at f_s=2 Khz

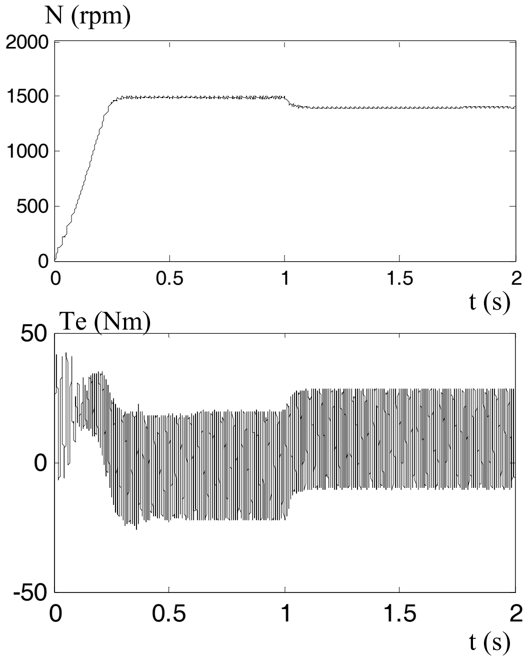
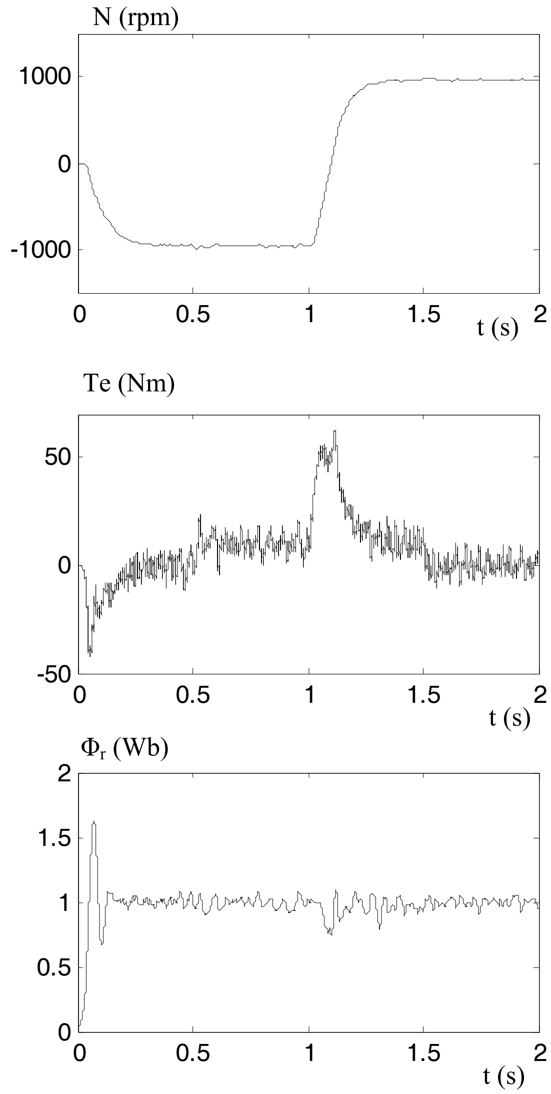


Fig. 8 Starting of SPIM fed from a matrix converter at :f_s=2Khz , q=0.866



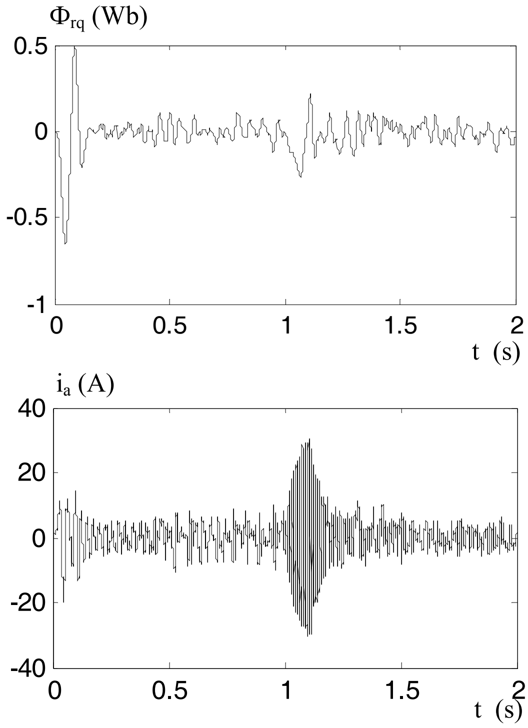


Fig. 9 Simulation results of the direct field oriented control of SPIM fed from a matrix converter at :f_s=2Khz , q=0.866

5. CONCLUSION

Vector control of six-phase induction machine fed from a six-phase matrix converter modelling and simulation have been described. The main topics discussed in the paper were:

- review of six-phase matrix converter;
- switching angles calculation;
- converter modelling and simulation;
- field oriented control.

To our knowledge, this is the first time that the vector control of six-phase induction machine supplied from a six-phase matrix converter has been simulated, this being the main contribution of the paper. High performances of the direct vector control are achieved with the use of six-phase matrix converter. According to the simulation results obtained, the control algorithm presented is advisable for the establishment in the high power applications. The next step of this research will be the realization of the motor drive.

APPENDIX

SIX-PHASE INDUCTION MACHINE PARAMETERS	
n°. of poles	2
Rated voltage, current	220 V , 3.64 A
Rated speed	1500 rpm
Stator , Rotor resistance (R_s , R_r)	4.8 Ω , 3.8 Ω
Stator , Rotor inductance (L_s, L_r)	27 mH , 27 mH
Mutual inductance (M)	26 mH

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