5-phase AC Induction Motor Rotor Flux Oriented Control with Space Vector Modulation Technique

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Abstract

The paper deals with the analysis of the rotor flux oriented control with space vector modulation technique for a five phase induction motor drive. The speed control using the rotor flux oriented control (RFOC) with or without speed sensor uses proportional integral controlled technique which make it possible to achieve satisfactory goals on the torque dynamics and flux. Simulated results on a five phase induction motor drive are displayed to validate the feasibility and the effectiveness of the proposed strategy.

Keywords:
Multi-phase, Space Vector Modulation, Flux oriented control, proportional integral, Induction motor.

1-Introduction

With the great development which knew the power electronic, expressing in the realization of statics converters (voltages inverters) with component (IGBT) commutating in very high frequencies and can provide variable output voltage.

Multi-phase motor drives have been studied from more than thirty years. Since the last two years, the interest has grown so that some international power electronic conferences have hosted sessions on the multiphase motor drives [1]. The multiphase motor drive has many advantages compared with the traditional three-phase motor such as reducing amplitude of torque and current pulsation, greater fault tolerance, also the multiphase motor has ability to reduce the stator current without increasing the stator voltage[2-3-

5-6].Because of those advantages numerous applications used the multiphase motor in particular the five-phase induction motor such winders and electric vehicles, aerospace, naval applications, papers mills and in textile manufacturing [4]. However, the state variables of five-phase induction motor are not easily measurable and they are dependent on the machine parameters. There are many strategies to control the five-phase induction motor; one of the most popular control strategies of the five-phase IM is RFOC (rotor flux oriented control) proposed since long time by Blaschke. The principle of the RFOC is to transform the five-phase induction motor into a system of decoupled equations. However the d-q axis reference frame currents contribute toward torque and flux production and the x-y components remaining zero. The goal of the RFOC is to make the electromagnetic torque similar of a dc machine then the flux and torque can be controlled independently by controlling the d and q components of stator currents.
The objective of this paper is to present the performances of the rotor flux oriented control of five motor (RFOC).

2-Modeling of the five phase inverter

The structure of a five phase voltage source inverter feeding a star-connected load shown in figure.1

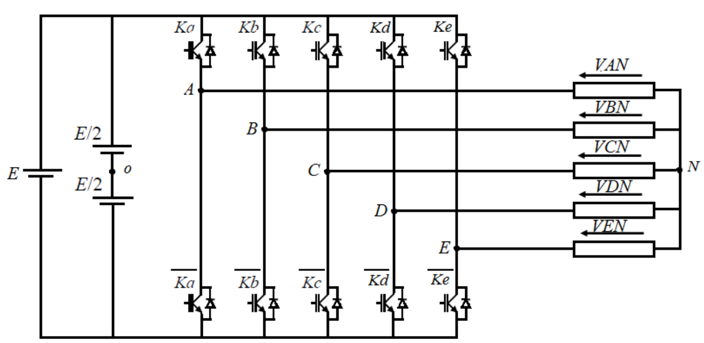

Figure 1.Structure of five phase voltage source inverter

In this paragraph, we will model the inverter whose the switches state can be defines by five Boolean $S_i (i = A, B, C, D, E)$.

- $S_i = 1$: When the switch top is closed and that of bottom is opened.
- $S_i = 0$: When the switch top is opened and that of bottom is closed.

Under these conditions we can write the voltages according to the control signals and taking account of the fictitious points'o'.

$$V_{io} = E(S_i - \frac{1}{2}) \quad (1)$$

$$\begin{pmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \\ V_{DN} \\ V_{EN} \end{pmatrix} = \frac{1}{5} \begin{pmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{pmatrix} \begin{pmatrix} V_{AO} \\ V_{BO} \\ V_{CO} \\ V_{DO} \\ V_{EO} \end{pmatrix} \quad (2)$$

(1) and (2) give:

$$\begin{pmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \\ V_{DN} \\ V_{EN} \end{pmatrix} = \frac{E}{5} \begin{pmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{pmatrix} \begin{pmatrix} S_A \\ S_B \\ S_C \\ S_D \\ S_E \end{pmatrix} \quad (3)$$

Space vector modulation

The principle of this method is to bring the five phase system to the two planes using Concordia transform.

$$\begin{pmatrix} V_o \\ V_d \\ V_q \\ V_x \\ V_y \end{pmatrix} = \sqrt{\frac{2}{5}} . \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \cos\frac{2\pi}{5} & \cos\frac{4\pi}{5} & \cos\frac{6\pi}{5} & \cos\frac{8\pi}{5} \\ 0 & \sin\frac{2\pi}{5} & \sin\frac{4\pi}{5} & \sin\frac{6\pi}{5} & \sin\frac{8\pi}{5} \\ 1 & \cos\frac{4\pi}{5} & \cos\frac{8\pi}{5} & \cos\frac{12\pi}{5} & \cos\frac{16\pi}{5} \\ 0 & \sin\frac{4\pi}{5} & \sin\frac{8\pi}{5} & \sin\frac{12\pi}{5} & \sin\frac{16\pi}{5} \end{pmatrix} \begin{pmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \\ V_{DN} \\ V_{EN} \end{pmatrix} \quad (4)$$

Where V may represent voltage, current, or flux linkage. Transforming the machine-variable voltage and flux linkage equations to the arbitrary reference frame gives traditional d-q model which has two axes (*d-q)* and one zero sequence that are used to represent the original five phase induction machine. The model has been split into three parts; one part is the decoupled *d-q* model, which has similar form as the three – phase model. The second part *x-y* equal zero and the third part o equal zero since $V_{AN}+V_{BN}+V_{CN}+V_{DN}+V_{EN}=0$ (5)

There are 2^5=32 possible switch configurations. For each sequence (i, e., in each d-q plane).

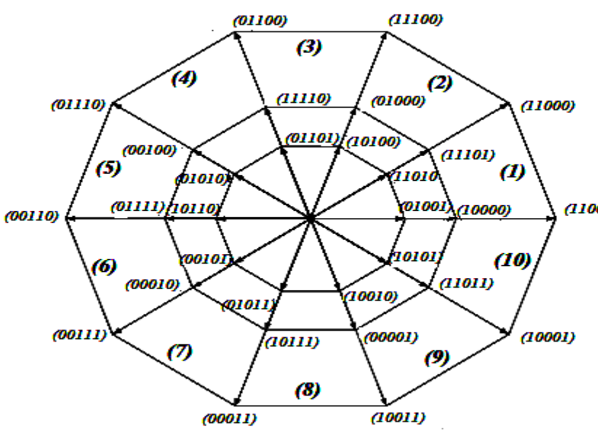

Fig 2. Phase voltage space vectors of a five-phase in d-q plane

The whole of 32 vectors which the inverter can impose currency in 4 types of vectors.

- Null vectors: $\overrightarrow{V_0}$ and $\overrightarrow{V_{31}}$.
- Vectors of module equal $1.618 * E * \sqrt{\frac{2}{5}}$
- Vectors of module equal $0.618 * E * \sqrt{\frac{2}{5}}$
- Vectors of module equal $E * \sqrt{\frac{2}{5}}$

The reference voltage vector can be written:

$$\overrightarrow{V_{ref}} = \sqrt{\frac{2}{5}}\left(V_{AN} + aV_{BN} + a^2V_{CN} + a^3V_{DN} + a^4V_{EN}\right) \quad (6)$$

Where:

$$a = \exp j\frac{2\pi}{5}$$

Following the substitutes of (3) in (6), one can obtain:

$$\overrightarrow{V_{ref}} = \sqrt{\frac{2}{5}}E(S_A + aS_B + a^2S_C + a^3S_D + a^4S_E) \quad (7)$$

The reference voltage vector can be written as:

$$\overline{V_{ref}} == \frac{1}{T_e}(T_i\overline{V_i} + T_{i+1}\overline{V_{i+1}}) \quad (8)$$

$$T_e = T_i + T_{i+1} + T_0 \quad (9)$$

Where:

T_e : Switching period

T_i: Application time of $\overline{V_i}$ vector

T_{i+1}: Application time of $\overline{V_{i+1}}$ vector

T_0: Application time of zero vectors ($\overline{V_o}$ and $\overline{V_{31}}$).

$\overline{V_i}$ and $\overline{V_{i+1}}$ are two vectors which delimit the sector *i* where is the reference voltage vector $\overrightarrow{V_{ref}}$.

Then $\overline{V_i}$ and $\overline{V_{i+1}}$ can be written as:

$$\begin{cases} \overline{V_i} = V_i \exp(j(i-1)\frac{\pi}{5}) \\ \overline{V_{i+1}} = V_i \exp(j(i)\frac{\pi}{5}) \end{cases} \quad (10)$$

By setting (10) in (8), one can obtain:

$$\overline{V_{ref}} = V_i(\frac{T_i}{T_e}\exp(j(i-1)\frac{\pi}{5}) + \frac{T_{i+1}}{T_e}\exp(j(i\frac{\pi}{5}))) \quad (11)$$

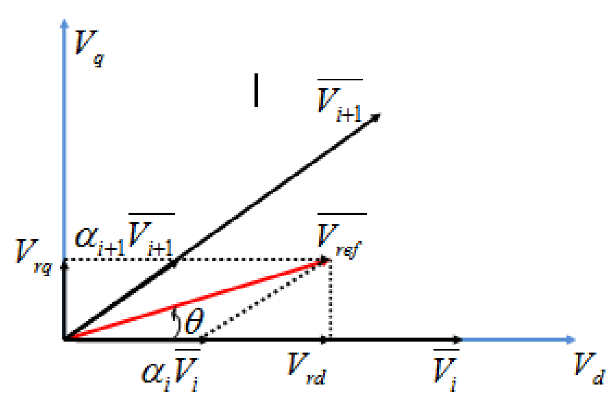

Fig.3. Approximation of the reference voltage vector

The definition (11) can be expressed as:

$$\begin{cases} \left|\overline{V_r}\right| .T_e \cos(\theta - i\frac{\pi}{5}) = V_i (T_i \cos(\frac{\pi}{5}) + T_{i+1}) \\ \left|\overline{V_r}\right| .T_e \sin(\theta - i\frac{\pi}{5}) = -V_i T_i \sin(\frac{\pi}{5}) \end{cases} \quad (12)$$

After development of the system (12), the duty-cycles can be written as follows:

$$\begin{cases} \alpha_i = \dfrac{\sin(i\frac{\pi}{5})V_{rd} - \cos(i\frac{\pi}{5})V_{rq}}{V_i \sin(\frac{\pi}{5})} \\ \alpha_{i+1} = \dfrac{\cos((i-1)\frac{\pi}{5})V_{rq} - \sin((i-1)\frac{\pi}{5})V_{rd}}{V_i \sin(\frac{\pi}{5})} \end{cases} \quad (13)$$

3-Modeling of a five-phase induction motor

Several assumptions of general theory of electrical drives present at the time of modeling of five induction motor. Such as, constant air-gap, the spatial displacement between two consecutive phases is 72 degrees; the rotor winding has the same proprieties as the stator winding, linearity of the magnetic circuit and sinusoidal spatial distribution on the field.

Under those assumptions the five-phase IM model is presented in a reference rotating frame (d-q) and (x-y) as:

$$\begin{cases} \dfrac{di_{isd}}{dt} = -\alpha i_{isd} + \omega_s i_{sq} + \beta\varphi_{rd} + \gamma\omega_r\varphi_{rq} + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{isq}}{dt} = -\omega_s i_{sd} - \alpha i_{sq} - \gamma\omega_r\varphi_{rd} + \beta\varphi_{rq} + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{di_{sx}}{dt} = -\eta i_{sx} - \dfrac{1}{L_{ls}} v_{sx} \\ \dfrac{di_{sy}}{dt} = -\eta i_{sy} - \dfrac{1}{L_{ls}} v_{sy} \\ \dfrac{d\varphi_{rd}}{dt} = L_m \lambda i_{sd} - \lambda\varphi_{rd} + \omega_g \varphi_{rq} \\ \dfrac{d\varphi_{rq}}{dt} = L_m \lambda i_{sq} - \lambda\varphi_{rq} - \omega_g \varphi_{rd} \\ \dfrac{d\varphi_{rx}}{dt} = -\mu\varphi_{rx} \\ \dfrac{d\varphi_{ry}}{dt} = -\mu\varphi_{ry} \\ \dfrac{d\omega_r}{dt} = \dfrac{P}{J}(C_{em} - C_r) - \dfrac{f}{J}\omega_r \end{cases} \quad (14)$$

C_r: Load torque

The state variables are the stator currents $(i_{sd}, i_{sq}, i_{sx}, i_{sy})$, the rotor fluxes $(\varphi_{rd}, \varphi_{rq}, \varphi_{rx}, \varphi_{ry})$ and the electrical rotor speed ω_r . The stator voltages $(v_{sd}, v_{sq}, v_{sx}, v_{sy})$ and the slip frequency ω_g are considered as the control variables. With the constants defines as:

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

$$\eta = \frac{R_s}{L_{ls}},\ \lambda = \frac{R_r}{L_r} = \frac{1}{T_r};\ \mu = \frac{R_r}{L_{lr}};\ \sigma = 1 - \frac{L_m^2}{L_{s1} L_{r1}}$$

The electromagnetic torque expressed in terms of the state variables is given by:

$$C_{em} = \frac{PL_m}{L_r}\left(\varphi_{rd} i_{sq} - \varphi_{rq} i_{sd}\right) \quad (15)$$

The angle of transformation for stator quantities given by:

$$\theta_s = \int \omega_s dt = \int (\omega_r + \omega_g) dt \quad (16)$$

4-Rotor flux oriented control (RFOC)

The system is strongly coupled; indeed the components of the voltage vector v_{sd} and v_{sq} influence simultaneously the state variables i_{sd} and i_{sq}. We will place the axis in order to simplify the differential equations.

Assuming that d-axis is held by the rotor flux phasor, then $\varphi_{rd} = \phi_r$ and $\varphi_{rq} = 0$ (17)
The condition (17) gives:

$$\omega_g = \frac{L_m R_r}{L_r} \frac{i_{sq}}{\phi_r} \quad (18)$$

$$\omega_s = \omega_r + \frac{L_m R_r}{L_r} \frac{i_{sq}}{\phi_r} \quad (19)$$

$$C_{em} = \frac{PL_m}{L_r} \phi_r i_{sq} \quad (20)$$

$$T_r \frac{d\phi_r}{dt} + \phi_r = L_m i_{sd} \quad (21)$$

These expressions show that the flux depends only on the component i_{sd} and the torque depends on the component i_{sq}. However the voltages v_{sd} and v_{sq} influence in the same time on i_{sd} and i_{sq} thus on the flux and torque, from where it came the idea to add the compensation terms in order to return the *d* and *q* axis are completely independent.

Then v_{sd} and v_{sq} can be written as follows:

$$\begin{cases} v_{sd} = (R_s + p\sigma L_s) i_{sd} - \omega_s \sigma L_s i_{sq} - \dfrac{L_m R_r \phi_r}{L_r^2} \\ v_{sq} = (R_s + p\sigma L_s) i_{sq} + \omega_s \dfrac{L_m}{L_r} \phi_r + \omega_s \sigma L_s i_{sd} \end{cases} \quad (22)$$

Where the compensation terms given by:

$$\begin{cases} e_{sd} = -\omega_s \sigma L_s i_{sq} - \dfrac{L_m R_r \phi_r}{L_r^2} \\ e_{sq} = \omega_s \dfrac{L_m}{L_r} \phi_r + \omega_s \sigma L_s i_{sd} \end{cases} \quad (23)$$

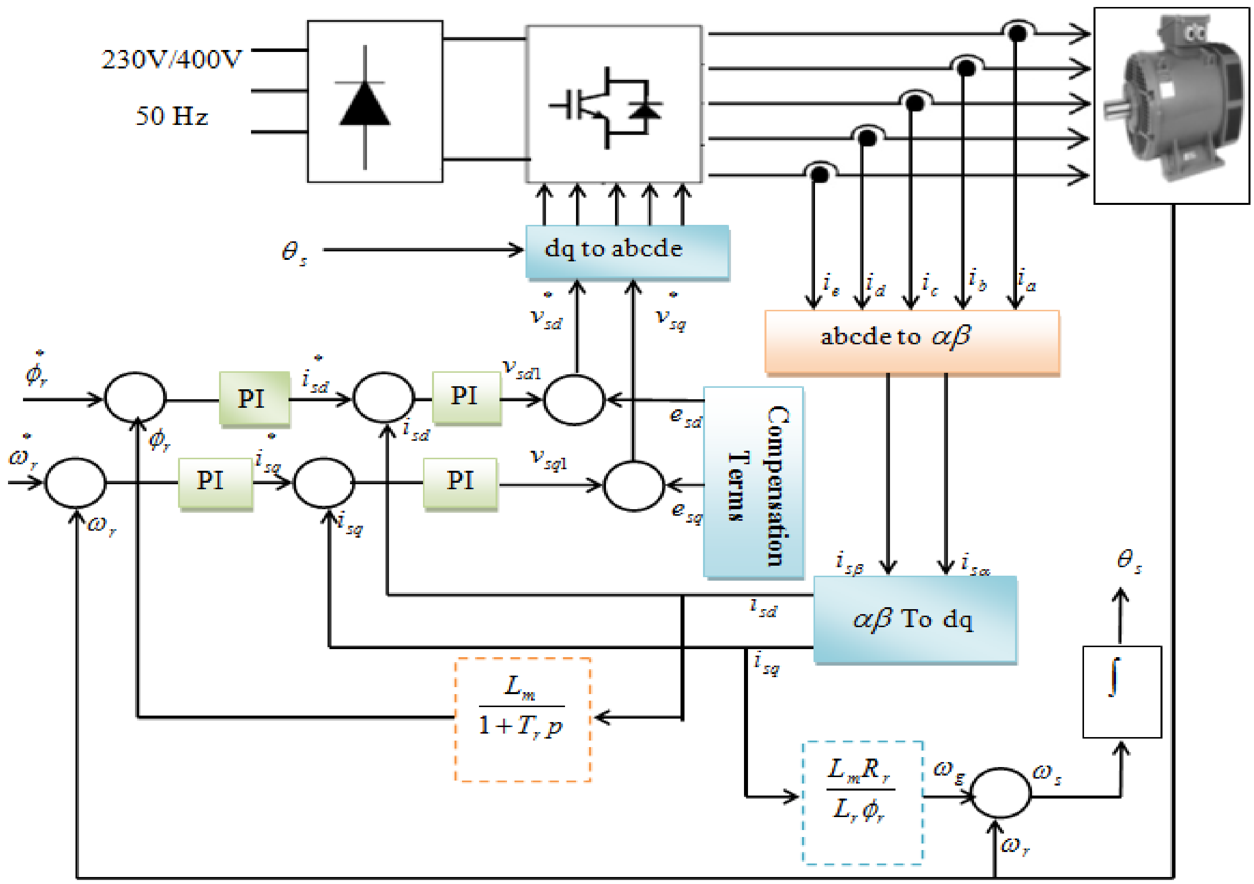

Figure.4. Rotor flux oriented control for a five-phase induction motor (Symbol (*) denotes references and parameters of the controller

The reference currents are expressed as follows:

$$\begin{cases} i_{sd}^{*} = i_{sn} = \dfrac{\phi^{*}}{L_m} \\ i_{sq}^{*} = \dfrac{L_r}{PL_m \phi^{*}} C_{em}^{*} \\ i_{sx}^{*} = 0 \\ i_{sx}^{*} = 0 \end{cases} \qquad (24)$$

The currents flowing in the plane d-q are responsible for creation of the rotating field in the air gap of the machine; on the other hand x-y components are responsible for the additional losses in distributed-winding machines [4].

5-Simulation results

It is clear that the line-to-line load voltages have 3 levels waveforms $(0,\pm E)$ similar of the three-phase. However; the line-to-neutral load voltage appears as a five-level waveform $\left(0,\pm\frac{2}{5}E,\pm\frac{3}{5}E\right)$

The line-to-neutral load VAN and the line-to-Line load voltages VAB are represented in the below figures.

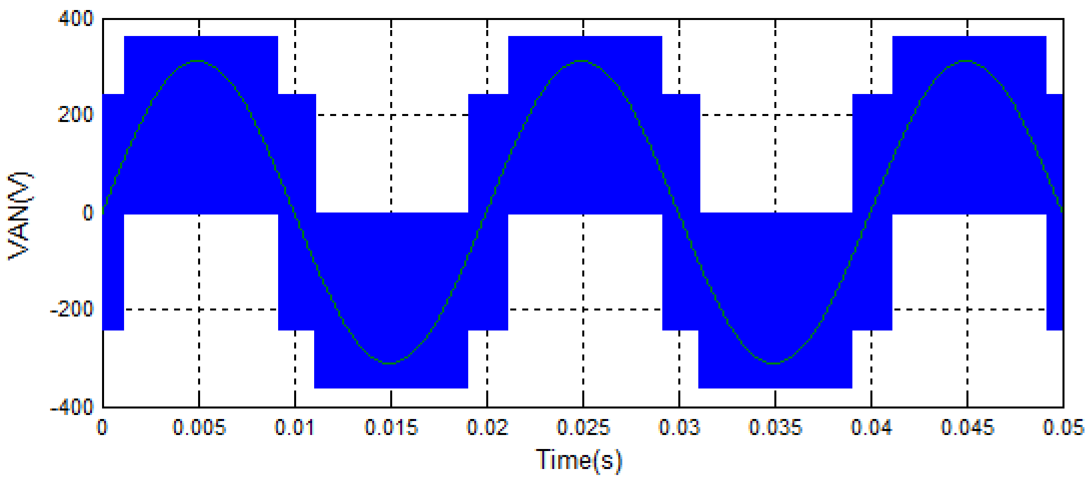

Fig.5. Line-to-neutral load voltage waveform (VAN)

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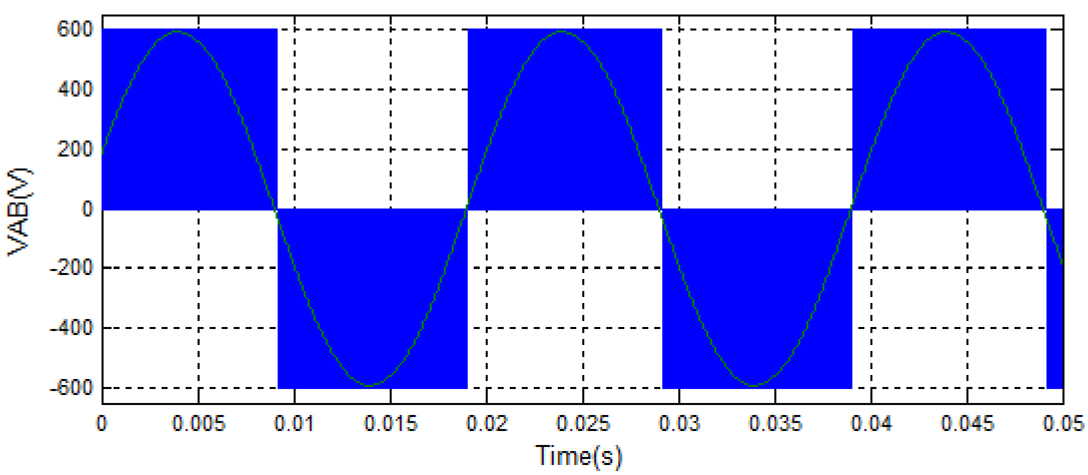


Fig.6. Line-to-line load voltage waveform(VAB)

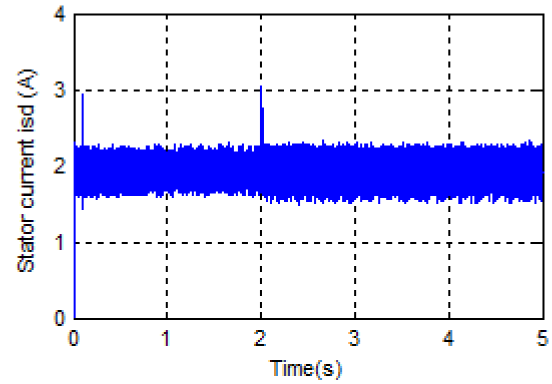
This strategy of modulation makes possible to obtain the root mean square (rms) voltages superiors of those obtained by the intersective modulation and led to the achievements software compatible with the constraints of calculation in real times of the electric ac motor drives.

The numerical simulation carried out on Matlab simulink of five-phase voltage source inverter provides a balanced load of five-phase which confirms the effectiveness of this strategy.
However, this five-phase voltage source inverter will use to control a five-phase induction motor through the space vector modulation strategy.

Speed profile 1

The reference speed and the load torque are step applied respectively at t=0.1s and t=2s.

Fig.7. displays the simulation results for the reference and real speed, reference and real torque, reference and real rotor flux, stator currents compounds i_{sd} and i_{sq}, stator phase's currents and speed and rotor flux error.



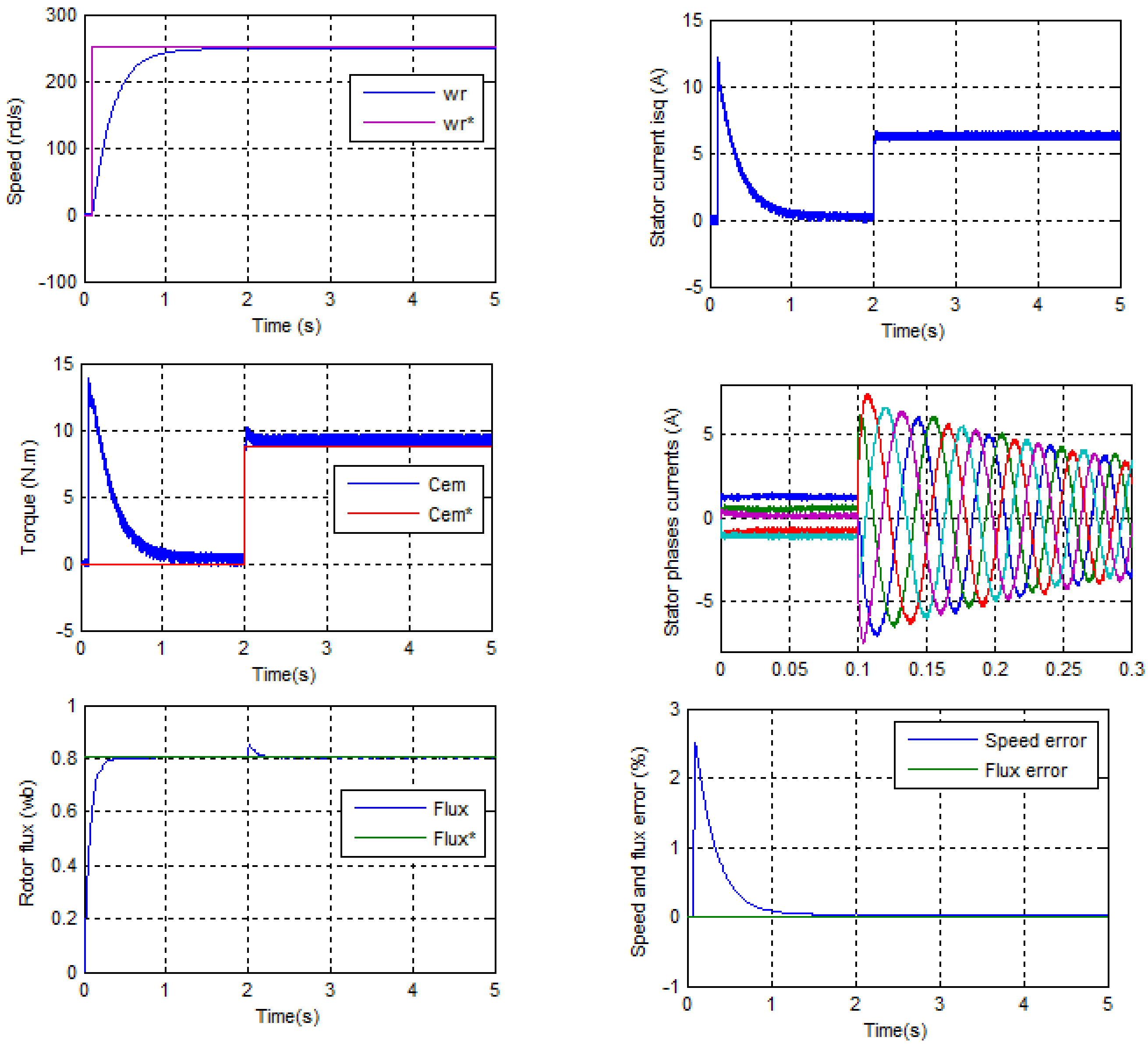
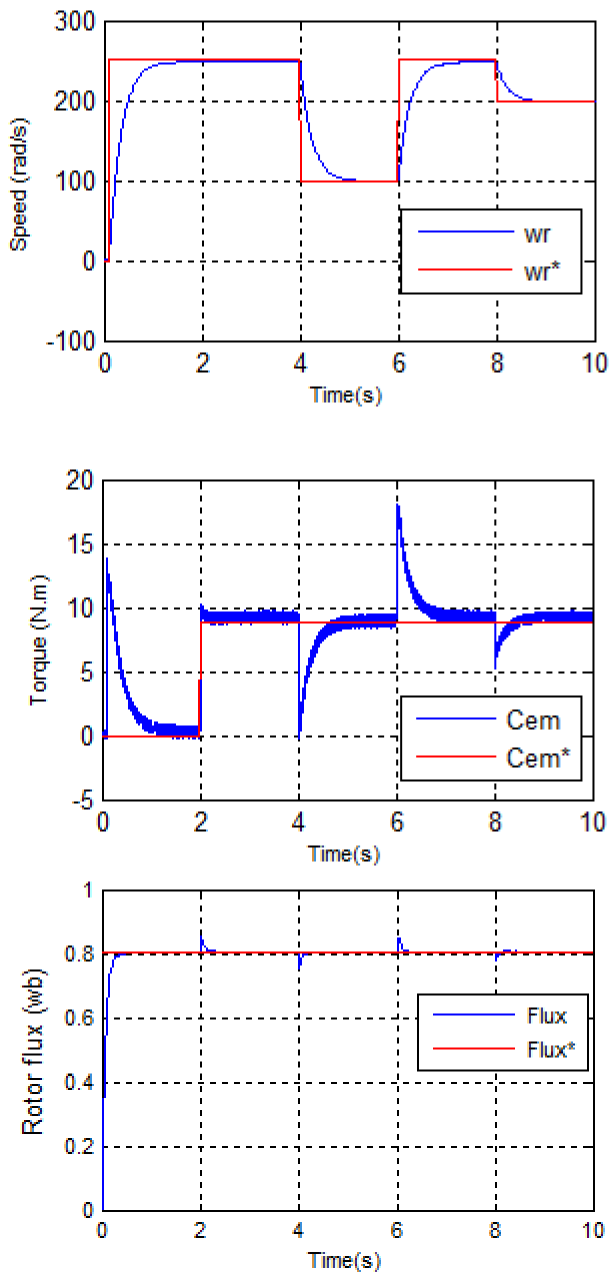


Fig.7. RFOC of a five-phase induction motor (speed profile 1)

Speed profile 2

The reference speed is variable (251.327rad/s at t=0.1s, 100rad/s at t=4s, 251.327rad/s at t=6 and 200rad/s at t=8s) and the load is a step at t=2s. Fig.8. displays the simulation result.



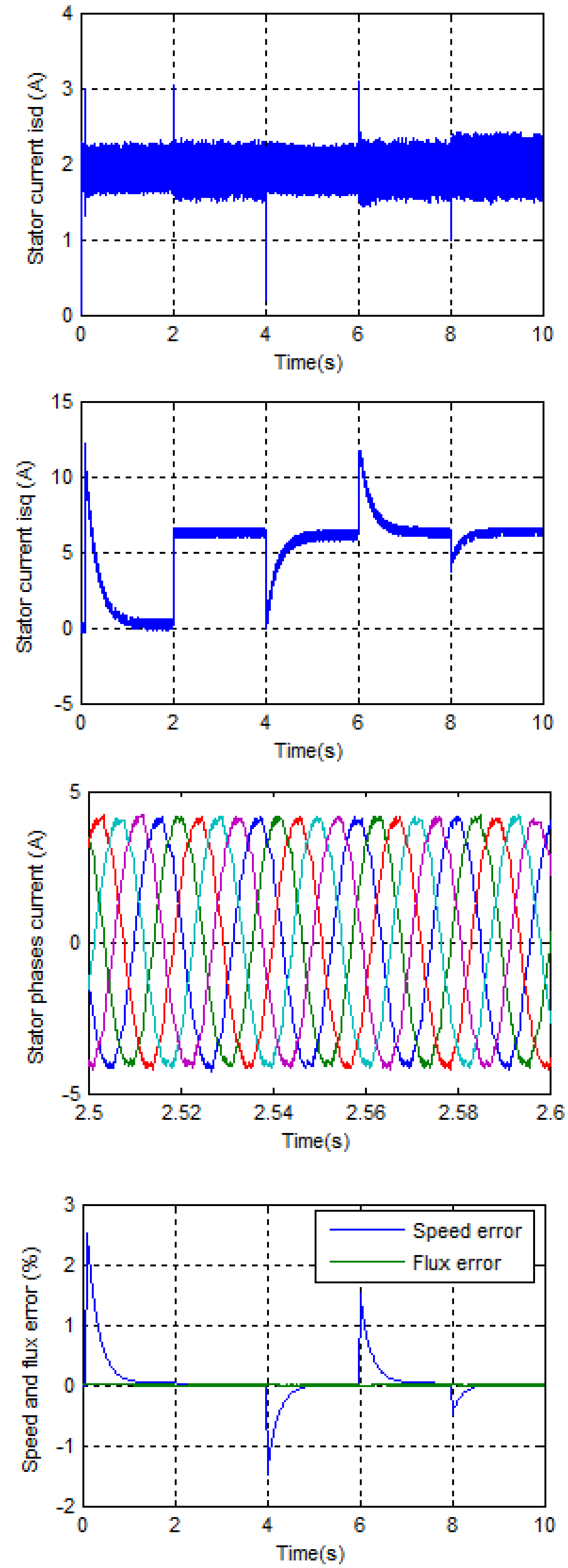
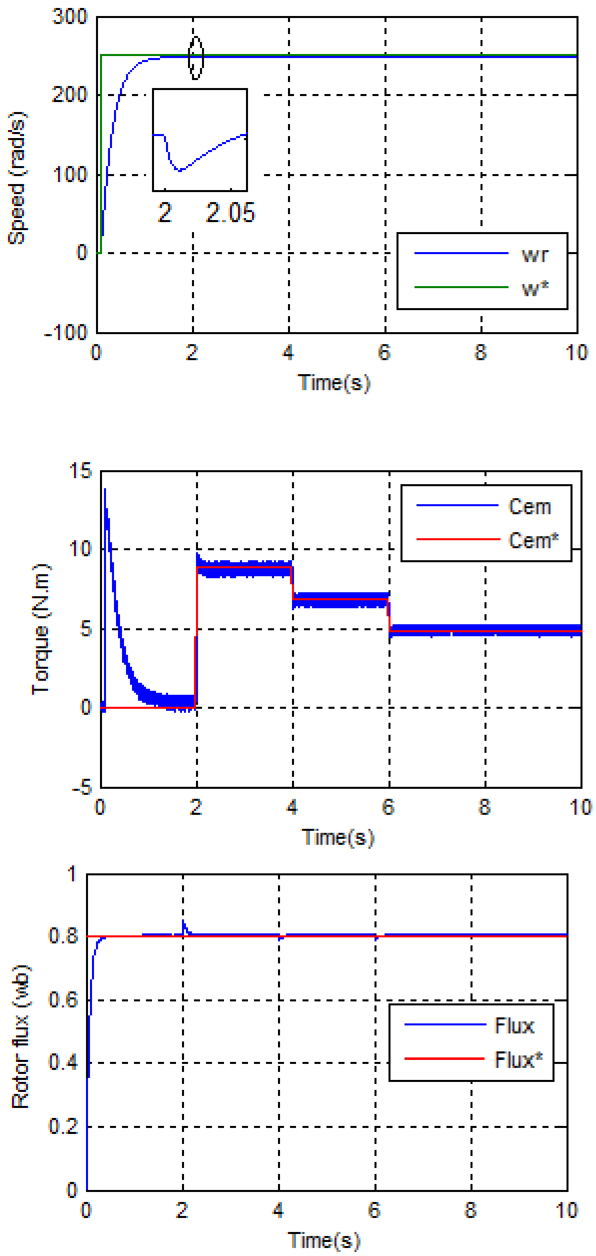


Fig.8. RFOC of a five-phase induction motor (speed profile 2)

Variable Load torque Profile

The reference speed is step applied at t=0.1s and the load torque is variable (8.33N.m at t=2s, 6.33N.m at =4s and 4.33 at t=6s).
Fig.9. displays the simulation result



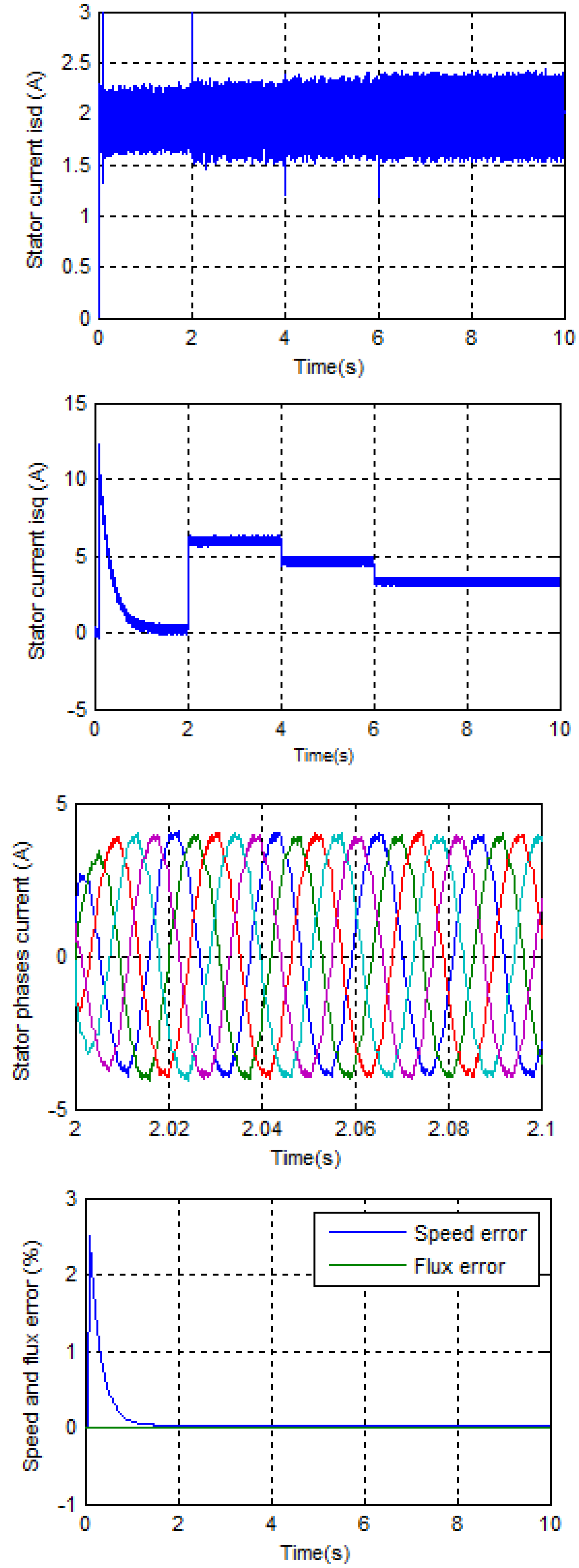


Fig.9. RFOC of a five-phase induction motor (variable Load torque profile)

We have illustrated the response of the five-phase induction motor under two different profile of speed and profile of load torque. According to the simulation results we can conclude many remarks. The real rotor flux and speed follow-up the reference quickly and perfectly, also the flux has unchanged after the initial transient because we considered that the motor parameters are constant.
However the torque response nearly follows the torque reference. The flux error is closely to zero even at the application moment of the load torque confirms well the decoupled control between torque and flux. Although, the application of the load torque causes inevitable dip in speed shows the proportionality between torque and speed, but the actual torque follows quickly the reference torque.

Conclusion

In this paper, we have developed the technique of rotor flux oriented control of a five phase induction motor, however this strategy allows to control the five-phase induction motor in a similar way as the dc motor, and we success to carry out the decoupled between the rotor flux and electromagnetic torque control. It is clear that the dynamic behavior, obtainable with the rotor flux oriented control is the same as it would have been had a three-phase machine be used. Indeed the rotor flux and electromagnetic torque are controlled respectively with the stator currents direct and indirect.
The simulation result shown the performance of the RFOC but this type of control has a weak point which acted of the bad robustness during the parameters variation. For this reason one resorts to other techniques base .on other concept of piloting as the non-linear control.

Machine parameters

$R_s = 10\Omega$	$C_r = 8.33 N.m$	$R_r = 6.3\Omega$
$In = 2.1A$	$L_{s1} = 0.46H$	$f = 0$
$L_{r1} = 0.46H$	$E = 600V$	$P = 2$

$L_m = 0.42 \quad L_{ls} = L_{lr} = 0.04H$
$\omega^* = 251.327 rad/s$
$\varphi^*(rms) = 0.5683 wb$

Nomenclature

d-q	d-and q-axis plane
x-y	x-and y-axis plane
v_{sd}, v_{sq}	stator voltages d-q axis compounds
v_{sx}, v_{sy}	stator voltages x-y axis compounds
i_{sd}, i_{sq}	stator currents d-q axis compounds
i_{sx}, i_{sy}	stator currents x-y axis compounds
$\varphi_{rd}, \varphi_{rq}$	rotor flux d-q axis compounds
$\varphi_{rx}, \varphi_{ry}$	rotor flux x-y axis compounds
P	number of pole pairs
J	inertia coefficient
L_{s1}	stator Cyclic inductance
L_{r1}	rotor cyclic inductance
L_{ls}	stator leakage inductance
L_{lr}	rotor leakage inductance
f	viscous friction coefficient
C_{em}, C_r	electromagnetic and load torque
L_m	mutual inductance
ω_s	electrical synchronous angular speed
ω_g	slip angular speed
σ	leakage coefficient
ω_r	electrical rotor angular speed
R_s	stator resistance
R_r	rotor resistance
p	laplace operator

Appendix A:

The proportional plus integral PI controller is used for currents, speed and flux control. The parameters of the PI are tuned to satisfy some performance, such as stability and precision. The PI is presented with the flowing equation:

$$R(p) = K_p + \frac{K_i}{p}$$

We determine the parameters K_p and K_i of the PI for each variable.
Where:

- Flux: $K_p = \frac{\rho}{L_m}$ et $K_i = \frac{\rho R_r}{L_m L_{r1}}$
- Speed : $K_p = \rho.f$ et $K_i = \frac{\rho.f^2}{J}$
- Currents i_{sd} et i_{sq} : $\begin{cases} K_p = \rho \dfrac{(R_s + R_r\left(\dfrac{L_m}{L_{r1}}\right)^2)}{\sigma L_{s1}} \\ K_i = \rho(R_s + R_r\left(\dfrac{L_m}{L_{r1}}\right)^2) \end{cases}$

Where $\rho > 1$

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