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Speed advanced control of Sensor less asynchronous machine squirrel cage

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ABSTRACT: This paper deals with an advanced technic which is based on state space model of squirrel asynchronous machine for the speed control. Many industrial applications need a good performance either in static operating or in dynamic one. Old technic gives moderate performance to the machine on various operating mode, in this reason, this article proposes a speed advanced control of sensorless asynchronous machine. The machine is fed by a two-level voltage inverter. Models of asynchronous machine and inverter are detailed for adequate use in the control methodology. Controller synthesis is used to determine the parameters value of the PI controller inserted on speed closed loop circuit. The controller is designed to fulfill the performance criteria on different cases. Simulations are worked out on MATLAB/Simulink to visualize the ability of the controller. Results on various operating mode of asynchronous machine are obtained and discussed.

KEYWORDS: field oriented control, asynchronous machine, two-level voltage inverter, PI, MATLAB/Simulink.

I- INTRODUCTION

The electric machine was invented during XIXth century, issued the invention of galvanic battery and the electromagnetic phenomenon discovery [1].

The asynchronous machine has a numerous advantages either in industry application or in its structure. Whereas it needs a strict control process and observation to handle with its functionalities. In fact, its multivariable and nonlinear nature makes it unobservable on low speeds. The speed variation must take an electromagnetic torque regard. It's necessary to decouple the flux from the electromagnetic torque by an adequate approach [2], [3]. In 1970's, Blaschke proposed to carry out this theory for three-phase machine control [4]. A modern sensorless control of variable speed induction motor was achieved [12].

In this document an asynchronous machine is controlled by a field oriented control process. The rotor speed is operated on three modes: with load, upper speed than nominal, reversed speed. A two-level three-phase inverter is used to provide a voltage source and enables the variation of the speed amplitude. First section gives the main part of asynchronous machine modeling that is used for the field oriented control. Second section presents the idea of how a three-phase converter is modeled. Then followed by the theory of field oriented control. Matlab/Simulink modeling and simulation results is exhibited in the last section.

II- ASYNCHRONOUS MACHINE STATE SPACE MODEL [10], [11]

Park transformation

In order to get an equation system with constant coefficients. The stator and rotor windings are transformed into equivalent orthogonal windings ds ,qs ,0s ; dr ,qr ,0r. Therefore, it's usual to use the Park transformation in which a unique matrix of transformation is defined for the currents,voltages and flux as:

$$[P(\theta)] = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} (1)$$

For the passage of three-phase system into two-phase one, we have:

$$\begin{cases} [V_{abc}] = [P(\theta)][V_{dq0}] \\ [i_{abc}] = [P(\theta)][i_{dq0}] \\ [\varphi_{abc}] = [P(\theta)][\varphi_{dq0}] \end{cases} (2)$$

The Park transformation inverse matrix is defined as follow:

$$[P(\theta)]^{T} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta - \frac{4\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) & 1 \end{bmatrix} \quad (3)$$

And we have:

$$\begin{gathered} [V_{dq0}] = [P(\theta)]^{T}[V_{abc}] \\ [i_{dq0}] = [P(\theta)]^{T}[i_{abc}] \qquad (4) \\ [\varphi_{dq0}] = [P(\theta)]^{T}[\varphi_{abc}] \end{gathered}$$

$$[\dot{X}] = [A][X] + [B][U] \qquad (5)$$

Where

[A] : System matrix

[X] : State vector

[B] : Control input gain matrix

[U] : Control matrix

III- STATE SPACE MODEL

Modeling process is an indispensable step before controlling one. Some hypotheses are to be considered. Park transformation is needed to fulfill the three to two axis transformations that is served in the computing task of control. The linearizedmodel of asynchronous machine can be presented in state space form as:

The asynchronous machine is fed by voltage source.The dynamic model state space for theasynchronous machine in d-q transformed field reference frame is depicted as follow:

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\sigma\tau_s} - \frac{1-\sigma}{\sigma\tau_r} & \frac{d\theta_s}{dt} & \frac{1-\sigma}{\sigma\tau_r M} & \frac{1-\sigma}{\sigma M}\left(\frac{d\theta_s}{dt} - \frac{d\theta}{dt}\right) \\ -\frac{d\theta_s}{dt} & -\frac{1}{\sigma\tau_s} - \frac{1-\sigma}{\sigma\tau_r} & -\frac{1-\sigma}{\sigma M}\left(\frac{d\theta_s}{dt} - \frac{d\theta}{dt}\right) & \frac{1-\sigma}{\sigma\tau_r M} \\ \frac{M}{\tau_r} & 0 & -\frac{1}{\tau_r} & \frac{d\theta}{dt} \\ 0 & \frac{M}{\tau_r} & -\frac{d\theta}{dt} & -\frac{1}{\tau_r} \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \qquad (6)$$

and $\sigma = 1 - \frac{M^2}{L_s L_r}$ is the total leak coefficient.

The state variables are i_{ds}, i_{qs}, φ_{dr}, φ_{qr}.

With

We have:

$$[B] = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}; \ [U] = \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix}$$

$$[A_1] = \begin{bmatrix} \alpha_1 & 0 & \alpha_2 & 0 \\ 0 & \alpha_1 & 0 & \alpha_2 \\ \frac{M}{\tau_r} & 0 & -\frac{1}{\tau_r} & 0 \\ 0 & \frac{M}{\tau_r} & 0 & -\frac{1}{\tau_r} \end{bmatrix};$$

$$[A_2] = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix};$$

$$[A_3] = \begin{bmatrix} 0 & 0 & 0 & \alpha_3 \\ 0 & 0 & -\alpha_3 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Where θ_s is the angle between stator and d-axis, θ is the angle between rotor and d-axis,

with

$$\alpha_1 = -\left(\frac{1}{\sigma\tau_s} + \frac{M^2}{\sigma L_s L_r \tau_r}\right)$$

$$\alpha_2 = \frac{M}{\sigma L_s L_r \tau_r}$$

$$\alpha_3 = \frac{M}{\sigma L_s L_r}$$

IV- POWER CONVERTER MODEL

A two-level three-phase power converter is the simplest multiple levels converter. The circuit is managed by six switches (k_{a1}, k_{a2}; k_{b1}, k_{b2}; k_{c1}, k_{c2}). The converter has two pairs of complementary controlled switches in each inverter leg as displayed in figure 1.Regarding that the two switches in each phase must not be on at the same time to avoid short circuiting the DC voltage source.

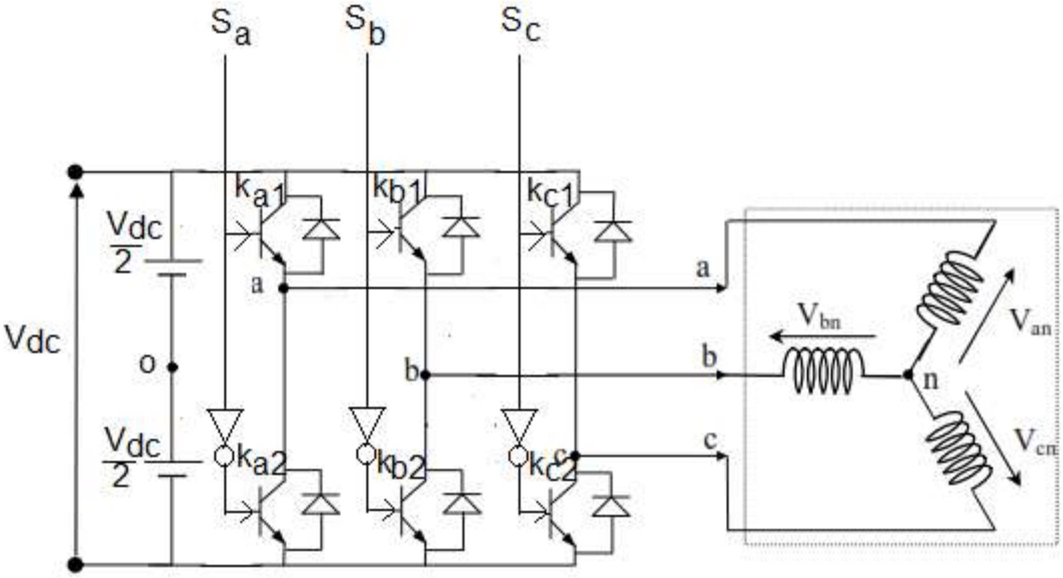

Figure 1: two-level voltage source inverter topology

The state of the switch is defined by the following conditions:

- If $S_i = 1$, K_{i1} is on and k_{I2} is off,
- If $S_i = 0$, K_{i1} is on off k_{I2} is on,

i = a, b, c

$$V_{ao} = \begin{cases} \frac{V_{dc}}{2}, S_a = 1 \\ -\frac{V_{dc}}{2}, S_a = 0 \end{cases} \rightarrow V_{ao} = K_a \frac{V_{dc}}{2} \qquad (8)$$

$$V_{bo} = \begin{cases} \frac{V_{dc}}{2}, S_b = 1 \\ -\frac{V_{dc}}{2}, S_b = 0 \end{cases} \rightarrow V_{bo} = K_b \frac{V_{dc}}{2} \qquad (9)$$

$$V_{co} = \begin{cases} \frac{V_{dc}}{2}, S_a = 1 \\ -\frac{V_{dc}}{2}, S_a = 0 \end{cases} \rightarrow V_{co} = K_c \frac{V_{dc}}{2} \qquad (10)$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} \mathrm{V_{ao}} \\ \mathrm{V_{bo}} \\ \mathrm{V_{co}} \end{bmatrix} \qquad (11)$$

$$\begin{bmatrix} \mathrm{V_{an}} \\ \mathrm{V_{bn}} \\ \mathrm{V_{cn}} \end{bmatrix} = \frac{1}{3}\frac{\mathrm{V_{dc}}}{2} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} \mathrm{K_a} \\ \mathrm{K_b} \\ \mathrm{K_c} \end{bmatrix} \qquad (12)$$

V- FIEL ORIENTED CONTROL

The field oriented control is a control implemented by using the direct component for the flux and the quadrature one for the electromagnetic torque, the choice of the appropriate (d, q) reference is essential and must be adapted to this control, ensures the decoupling of the flux and electromagnetic torque [5], [6], [7].The control aims at bringingthe asynchronous machine up to behavior like a DC motor by breaking up the stator current components i_{ds} and i_{qs}. This control is based on the choice of (d, q) reference which is linked to the field.

The field oriented control is implemented through two mains methods:

- Direct method was initiated by F.BLASCHKE.
- Indirect method was achieved by K.HASS.

This work deals with an indirect method which doesn't use the rotor flux amplitude but its position. It entails the use of rotor speed (position) sensor or estimator [8].This method is sensitive to the machine parameters variation due to the magnetic saturation and temperature variation, especially time constant of rotor [9].

VI- STRATEGY OF CONTROL

The control consists of keeping the rotor flux q-axis at zero in order to fulfill the orientation condition. Since the magnet flux is constant, thus the electromagnetictorque is linearly proportional to the q-axis current which is defined by the machine operating mode (with load or without load). The electromagnetic torque is obtained from the speed controller output. The rotor speed control is performed by closed loop control. As a result, accurate reference tracking and maximum torque can be gained in addition to high dynamic performance.

The electromagnetic torque equation is given by:

$$\mathrm{C_{em}} = \frac{3}{2}\mathrm{MP}\left(\mathrm{I_{qs}I_{dr}} - \mathrm{I_{ds}I_{qr}}\right) \qquad (13)$$

We take the flux equation to deduce the rotor current:

$$\mathrm{I_{dr}} = \frac{\varphi_{\mathrm{dr}} - \mathrm{MI_{ds}}}{\mathrm{L_r}} \qquad (14)$$

$$\mathrm{I_{qr}} = \frac{\varphi_{\mathrm{qr}} - \mathrm{MI_{qs}}}{\mathrm{L_r}} \qquad (15)$$

The electromagnetic torque becomes:

$$C_{em} = \frac{3}{2} P \frac{M}{L_r} \left(\varphi_{dr} I_{qs} - \varphi_{qr} I_{ds}\right) \qquad (16)$$

and assuming that:

$\varphi_{rd} = \varphi_r$ et $\varphi_{rq} = 0$

We finally have:

$$C_{em} = \frac{3}{2} P \frac{M}{L_r} \left(\varphi_r \wedge I_{qs}\right) \qquad (17)$$

VII- SPEED CONTROLLER

The objective of the control is to satisfy the required performance criteria as:

- Accuracy on tracking
- Accuracy on controlling: rising time, overshoot, stability.
- Robustness through disturbance: Load, moment of inertia.
- Sensibility on parameters variation.

In order to fulfill the criteria, PI controller is used and the transfer function is depicted as follow:

$$G(s) = k_p + \frac{k_i}{s} \qquad (18)$$

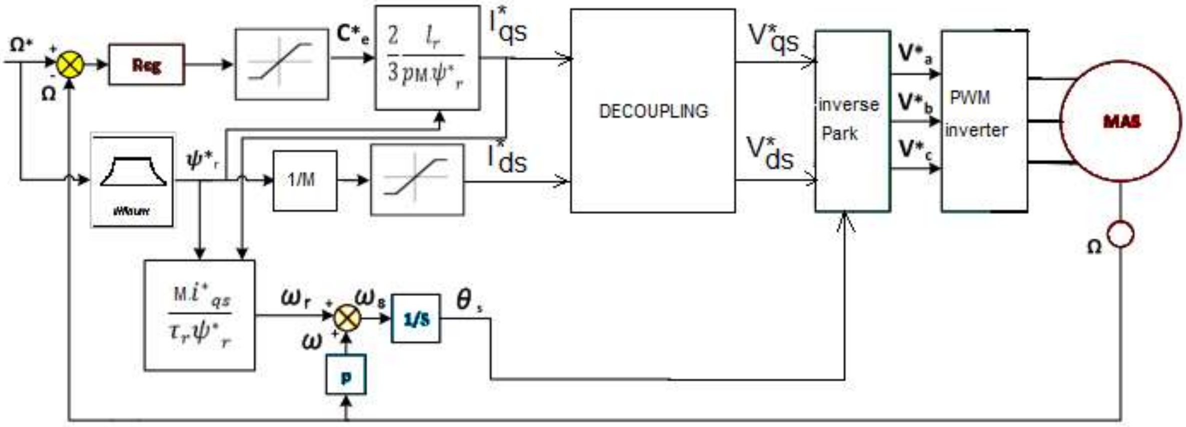

Figure 2: Indirect field oriented control

VIII- RESULTS AND DISCUSSION

Indirect field oriented control strategy for asynchronous machine was simulated with MATLAB/ Simulink, aimed at visualizing the behavior of the controller including its performance and weakness on different operating mode. Table 1 displays the parameters used for simulations.

Nominal power	¼ HP
Nominal speed	1770 RPM
Pole	4
Stator resistance	$R_s = 12,5\ \Omega$
Rotor resistance	$R_r = 7,2\ \Omega$
Stator leak inductance	$l_s = 0,02175$ H
Rotor leak inductance	$l_r = 0,02175$ H
Stator cyclic inductance	$L_s = 0,49925$ H
Rotor cyclic inductance	$L_r = 0,49925$ H
Mutual inductance	$M = 0,4775$ H
Moment of inertia	$J = 0,0022$ kg.m^2
Friction coefficient	$B = 0,001224$ Nm.s/rad
Proportional gain	$k_p = 0,1132$
Integrator gain	$K_i = 0,1652$

Table.1: parameters used for simulations.

a) OPERATING WITH LOAD

The asynchronous machine is operating in motor mode and is fed by a three-phase voltage source of 300V.A voltage inverter, which is very essential for the frequency converter, works with voltage Vdc = 300V. Switching frequency is selected $f_p = 3$ kHz.

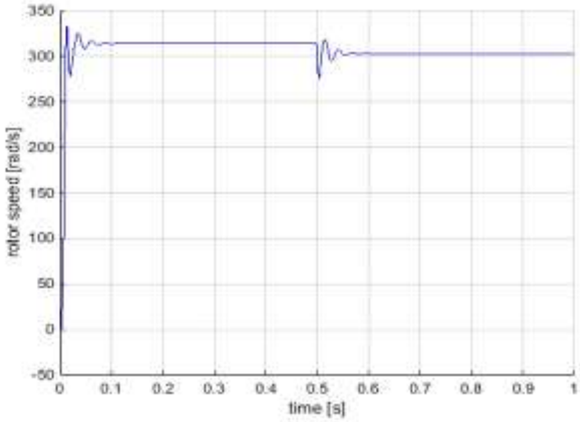

Figure 3: rotor speed

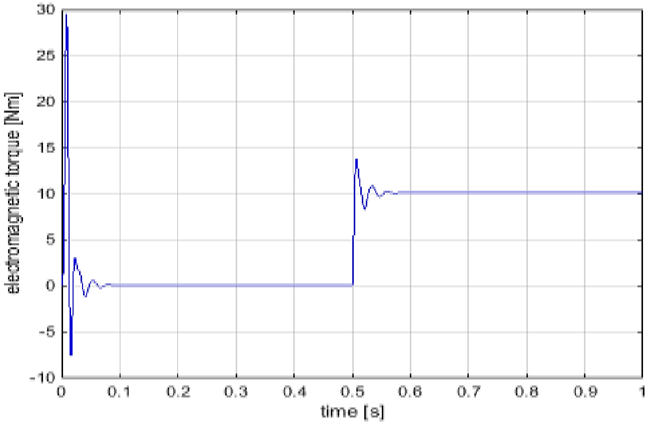

Figure 4: Electromagnetic torque

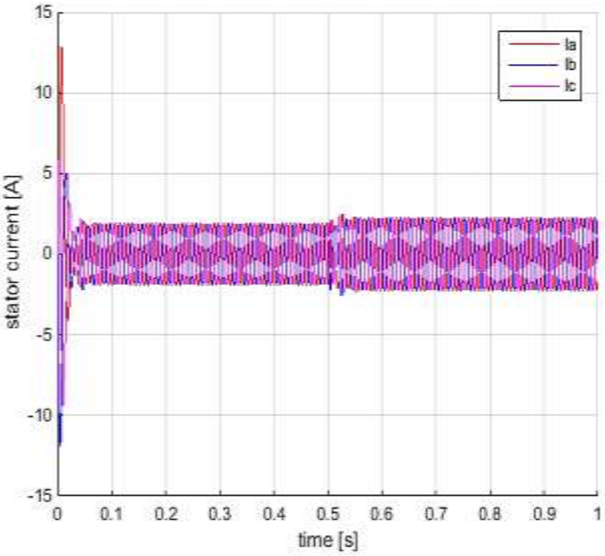

Figure 5: Stator current

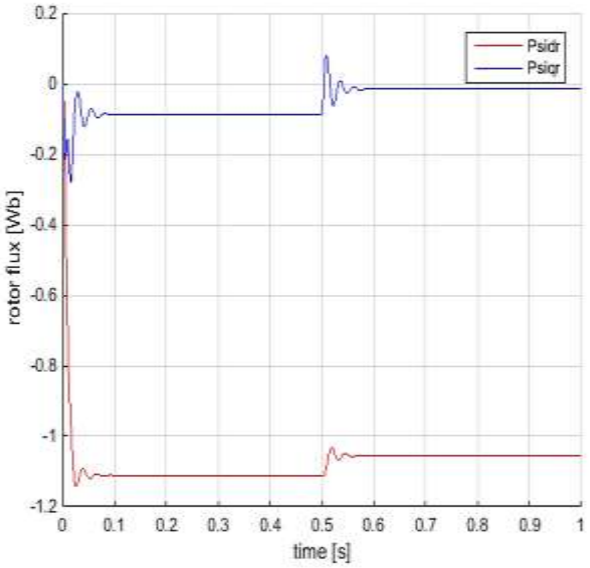

Figure 6: Rotor flux dq axis

Transient response: The peak value of the stator current reaches about 12 A (figure 5). The same observation is noticed on the value of electromagnetic torque waveform (figure 4) which gets to 28 Nm.

Steady state:A load 10 Nm (figure 4) is applied after 0.5s and the rotor speed decreases into 304 rad/s (figure 3), the stator current increases to 2.5 A (figure 5), increasing change is displayed on both flux dq axis values (figure 6).

b) OVERSPEED OPERATING OF INDIRECT FIELD ORIENTED CONTROL

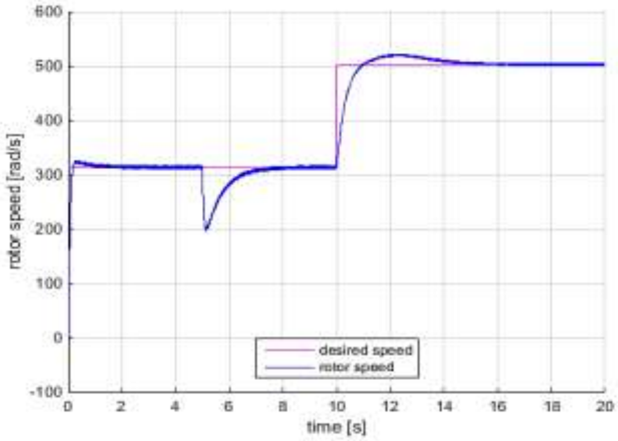

Figure 7: Rotor speed

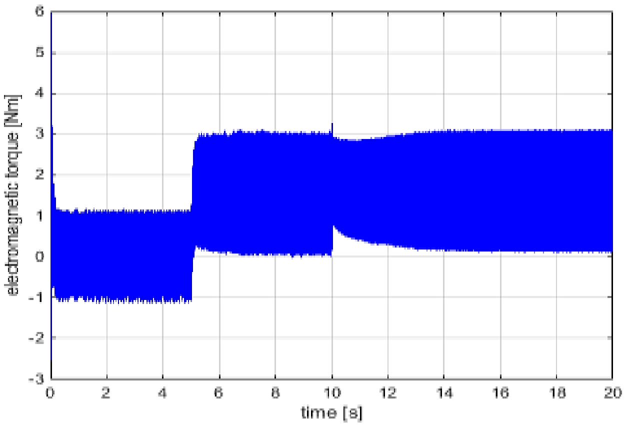

Figure 8: Electromagnetic torque

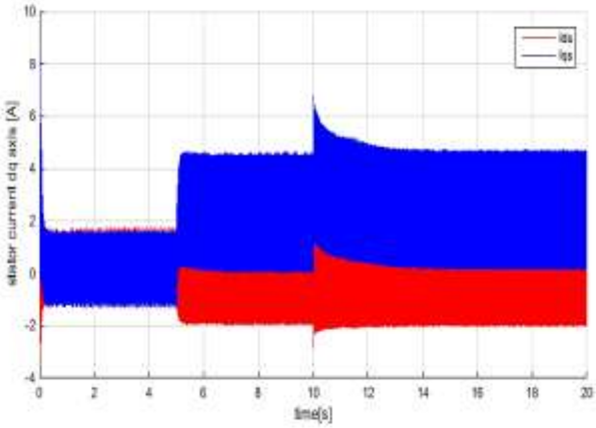

Figure 9: Stator current dq axis

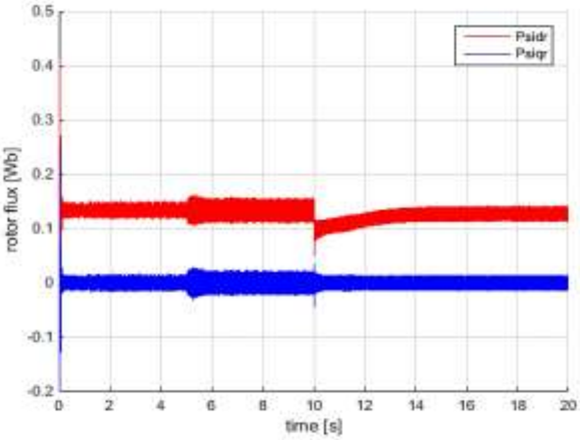

Figure 10: Rotor flux

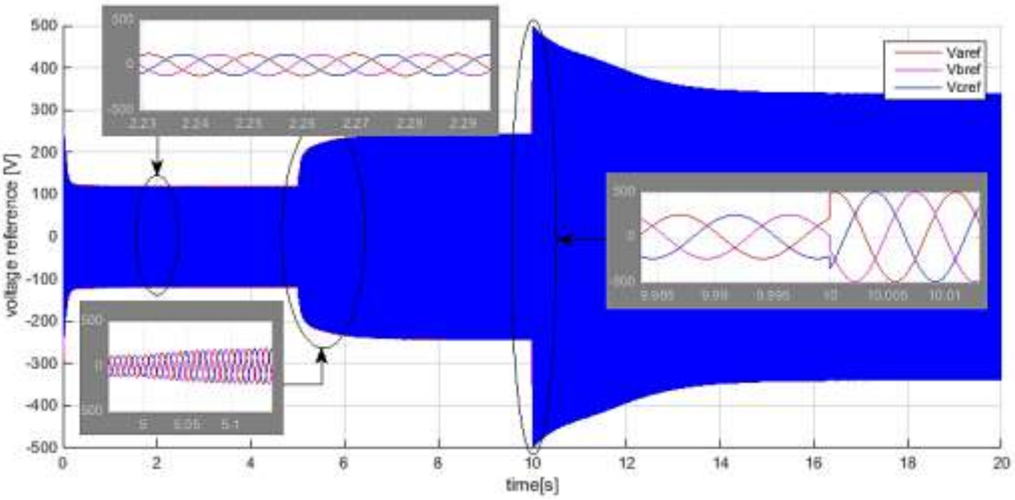

Figure 11: voltage reference

The asynchronous motor is powered by a three-phases two-level voltage converter sinus-triangle PWM controlled. The rotor speed reference is set to 314 rad/s.A constant value of flux is forced to the rotor.

Transient response : An acceptable overshoot is noticed on rotor speed (figure 7), the peak values of both parameters stator current and electromagnetic torque are reduced (figure 8, 9). Whereas, the flux dq axis peak values are increased (figure 10).

When a sudden change to 502 rad/s on speed reference is applied at 10s, a disturbance on stator current is noticed, the voltage reference (figure 11) is risen to340V preceded by a disturbance.

Steady state: at 5s, a load of 1.5 Nm is applied. The rotor speed waveform displays the reference tracking performance of the controller by quickly rejecting the disturbance at 5s (figure 7). The voltage reference is increased to 242.2V. At 10s, the speed reference is changed up to 502 rad/s. It takes 4s for the controller to reach the steady state and follow the desired speed. It’s seen that the Iqs and electromagnetic waveform have the same evolution (figure 8, 9). It’s noticed on the flux waveform that $\varphi_{qr} = 0$ and $\varphi_{qr} = \text{constante}$ (figure 10).

c) FIELD ORIENTED CONTROL OPERATING WITH SPEED INVERSION

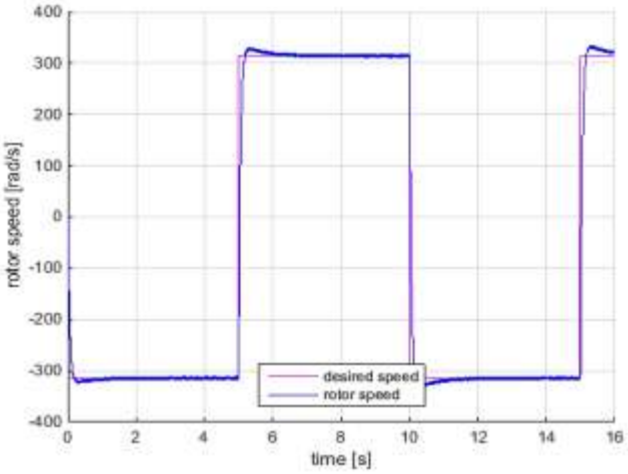

Figure 12: Rotor speed

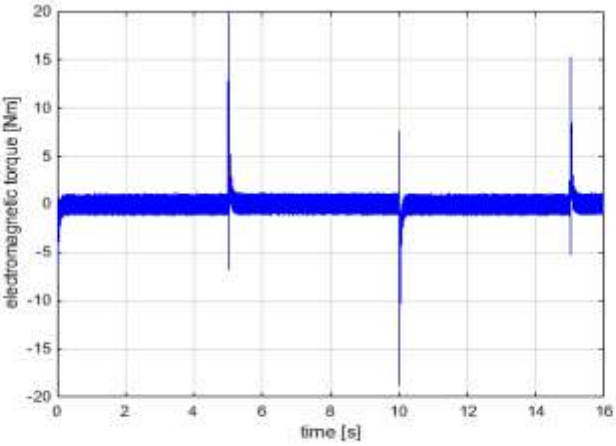

Figure 13: Electromagnetic torque.

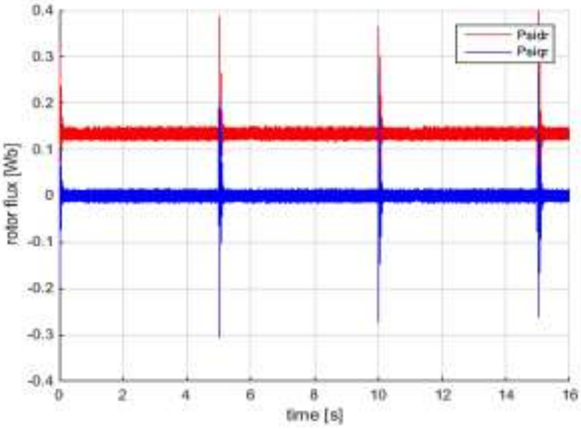

Figure 14: Rotor flux

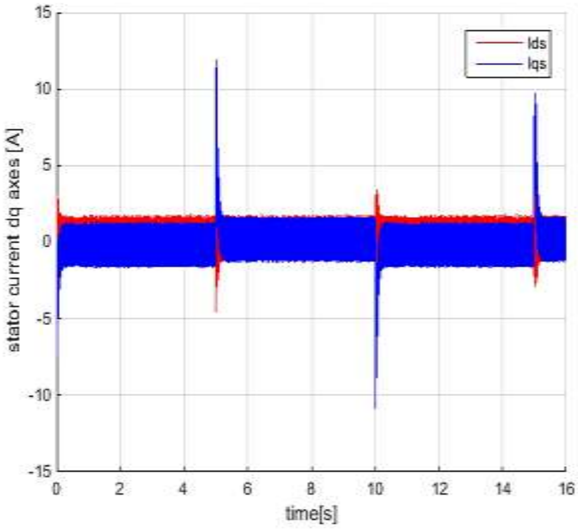

Figure 15: Stator current dq axis

The rotor speed reference is reversed without load. The figure 12 shows the performance of the controller of tracking the desired speed. At timewhen the speed is inversed, a peak of dynamic is observed on the electromagnetic torque, rotor flux and stator current due to the rotor inertia.

CONCLUSION

This work enables us to deepen the studies on indirect field oriented control of asynchronous machine. Asynchronous machine modeling was exhibited using the Park transformation. A two-level voltage inverter was used to permit the variation of the rotor speed by varying the voltage / frequency. Different cases of operating were implemented through simulation on MATLAB/Simulink. The results confirmed the performance and robustness of the proposed control. The controller proves a good behavior of rejecting a disturbance by load torque, ability of tracking the speed reference through a changing step speed in addition to the inversed speed reference. A high dynamic response and accurate stability were achieved by the controller.

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