Modeling of Electronic Speed Regulation in Hyposynchronous Cascade of The Ring Industrial Motor of The Bralima Company

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Abstract- *In this article, we present the models of the electronic speed regulation of the industrial ring motor by the modeling of the voltage inverter. These models are based on pulse width modulation; the switching times are determined by the intercession points between the carrier and the modulant. The switching frequency of the switches is set by the carrier. The motor is modeled from the voltages that we denote V_{an}, V_{bn} and V_{cn} and the inverter is controlled by logical quantities. The PWM control is very useful for the control of the asynchronous motor, based on the comparison between two signals, which one makes the generation of the sequences of the pulses.*

Keywords- Modelling, Electronic regulation, Speed in cascade, Hyposynchronous, Industrial motor to ring

I. INTRODUCTION

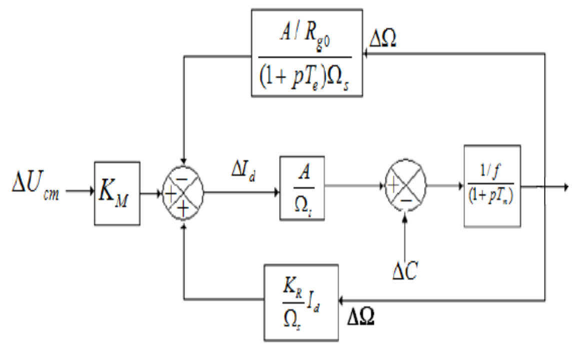
Conventional control, where the mains voltage is applied directly to the ring motor does not offer the possibility of varying the speed of said motor. The use of classic PI (Proportional Integral) or IP (Proportional Integral) regulators also do not offer the freedom of adjustment to operate at a speed above or below the limits of synchronism without any disturbance. The new ring motor control technology uses power electronics using variable speed drives. Mechanisms capable of varying the supply frequency of two motor fields (stator and rotor).

II. REGULATION DU MOTEUR

II.1 Equationsdes paramètres

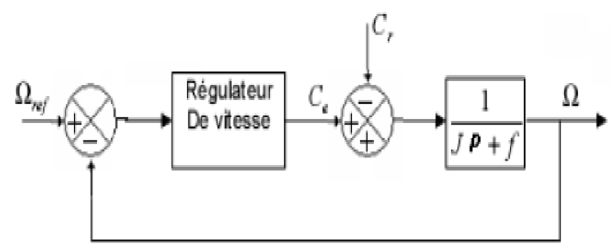
II.1.1 Régulation de la vitesse

It is a PI regulator containing a gain and an integrator and having as input the difference between the speed given by the machine at that moment.



Figures II.1 : Schéma synoptiques de régulation du moteur asynchrone

La boucle peut être simplifié par :



Figures II.2 :Schéma simplifié de la régulation du moteur asynchrone

$$\Omega = \frac{1}{f+J_p}\left(\frac{K_{p1}P + K_{i1}}{p}\right)\left(\Omega_{réf} - \Omega\right) - \frac{1}{f+J_p} C_r \quad (2.1)$$

Soit :

$$\Omega = \frac{K_p P + K_i}{J_p{}^2 + \left(K_{p1} + f\right)P + K_{i1}} \Omega_{réf} - \frac{p}{J_p{}^2 + \left(K_{p1} + f\right)P + K_{i1}} C_r \; (2.2)$$

So the closed loop transfer function is:

$$BF = \frac{\mathrm{K_{p1}P + K_{i1}}}{\mathrm{J_p}^2 + (\mathrm{K_{p1}} + f)\mathrm{P} + \mathrm{K_{i1}}} \quad (2.3)$$

Taking as the pole of BF:

$$\mathrm{P_1} = -\rho - j.\rho \; et \;\; \mathrm{P_1} = -\rho + j.\rho \quad (2.4)$$

So the denominator will have the following expression:

$$\mathrm{J_p}^2 + (\mathrm{K_{p1}} + f)\mathrm{P} + \mathrm{K_{i1}} = J.(p - \mathrm{p_1})(p - \mathrm{p_2}) = \mathrm{J_p}^2 - J (\mathrm{p_1} + \mathrm{p_2}).p + J.\mathrm{p_1 p_2} \quad (2.5)$$

In identifies, we find:

$$\begin{cases} \mathrm{K_{p1}} = 2.J\rho - f \\ \mathrm{K_{i1}} = 2.J\rho^2 \end{cases} \quad (2.6)$$

Pour $\rho = 35 \; on \; a \; \mathrm{K_{p1}} = 1.081$ et $\mathrm{K_{i1}} = 37.975$

II.1.2 Régulation du courant

From equation (2.7), we obtain the following equation:

$$\Delta \mathrm{I_d} = \mathrm{K_M} \Delta \mathrm{U_{cm}} - \frac{\mathrm{A}}{\frac{\mathrm{R_{g0}}}{1 + \mathrm{pT_e}}} \frac{\Delta\Omega}{\Omega_s} + \mathrm{I_{d0}K_R} \frac{\Delta\Omega}{\Omega_s} \quad (2.7)$$

Then we eliminate the component 1 + pT_e by the PI regulator where:

$$1 + \mathrm{pT_e} = \mathrm{K_{p2}} + P\mathrm{K_{i1}} \; (2.8)$$

$$\mathrm{T_e} = \frac{\mathrm{K_{p2}}}{\mathrm{K_{i1}}} = \frac{L}{\mathrm{R_{g0}}} \quad (2.9)$$

$$BO(\mathrm{I_d}) = \frac{A}{\mathrm{R_{g0}}} \frac{\Delta\Omega}{\Omega_s} \mathrm{K_{i2}} \frac{1}{p} = \frac{\tau}{p} \quad (2.10)$$

It is a first order equation which reaches 95% of its final value 3τ, that is to say:

$$t_{9\%} = 3\tau = 3 \frac{A}{\mathrm{R_{g0}}} \frac{\Delta\Omega}{\Omega_s} \mathrm{K_{i2}} \quad (2.11)$$

$$\Rightarrow \mathrm{K_{i2}} \frac{1}{3} = t_{9\%} \frac{\Omega_s}{\Delta\Omega} \frac{\mathrm{R_{g0}}}{A} \quad (2.12)$$

Et $\mathrm{K_{p2}} = \mathrm{T_e}.\mathrm{K_{i2}}$; soit $\mathrm{K_{i2}} = 0{,}087$ et $\mathrm{K_{p2}} = 0{,}2$

II.2.3Résolution par la méthode Runge-Kutta

II.2.3.1 Pour une seule équation

$$\begin{cases} F_1 = F(t_0, x_0, U_0) \\ t_1 = t + \frac{h}{2} \\ x_1 = t + \frac{h}{2} F_1 \\ U_1 = U(t_1) \end{cases} \quad (2.13)$$

$$\begin{cases} F_2 = F(t_1, x_1, U_1) \\ t_2 = t + \frac{h}{2} \\ x_2 = t + \frac{h}{2} F_2 \\ U_2 = U(t_2) \end{cases} \quad (2.14)$$

$$\begin{cases} F_3 = F(t_2, x_2, U_2) \\ t_3 = t + h \\ x_3 = t + hF_3 \\ U_3 = U(t_3) \end{cases} \quad (2.15)$$

$$F_4 = F(t_3, x_3, U_3) \quad (2.16)$$

$$x_{n+1} = x_n + h[F_1 + 2F_2 + 2F_3 + F_4] \quad (2.17)$$

II.2.3.2Pour deux équations

$$\begin{cases} t = t_0 \\ x = x_0 \\ U = U(t_0) \\ U' = U'(t_1) \end{cases} \quad (2.18)$$

$$f_1 = f_1(t_0, x_0, x'_0, U(t_0), U'(t_0)) \quad (2.18)$$

$$f_1{}' = f_1{}'(t_0, x_0, x'_0, U(t_0), U'(t_0)) \; (2.19)$$

$$\begin{cases} t = t_0 + \dfrac{h}{2} \\ x = x_0 + \dfrac{h}{2} f_1 \\ U = U\left(t_0 + \dfrac{h}{2}\right) \\ x' = x'_0 + \dfrac{h}{2} f \\ U' = U'\left(t_0 + \dfrac{h}{2}\right) \end{cases} \quad (2.20)$$

$$f_2 = f_2\left(t_0 + \frac{h}{2}, x, x', U, U'\right) \quad (2.21)$$

$$f_2' = f_2'\left(t_0 + \frac{h}{2}, x, x', U, U'\right) \quad (2.22)$$

$$\begin{cases} t = t_0 + \dfrac{h}{2} \\ x = x_0 + \dfrac{h}{2} f_2 \\ U = U\left(t_0 + \dfrac{h}{2}\right) \\ x' = x'_0 + \dfrac{h}{2} f_2' \\ U' = U'\left(t_0 + \dfrac{h}{2}\right) \end{cases} \quad (2.23)$$

$$f_3 = f_3\left(t_0 + \frac{h}{2}, x, x', U, U'\right) \quad (2.24)$$

$$f_3' = f_3'\left(t_0 + \frac{h}{2}, x, x', U, U'\right) \quad (2.25)$$

$$\begin{cases} t = t_0 + h \\ x = x_0 + h f_3 \\ U = U(t_0 + h) \\ x' = x'_0 + h f_3' \\ U' = U'(t_0 + h) \end{cases} \quad (2.26)$$

$$f_4 = f_4\left(t_0 + \frac{h}{2}, x, x', U, U'\right) \quad (22.7)$$

$$f_4' = f_4'\left(t_0 + \frac{h}{4}, x, x', U, U'\right) \quad (2.28)$$

II.2.4 Paramètres du moteur asynchrone

- ✓ Nominal power: 1.05 kW
- ✓ Nominal voltage: 220/380 V
- ✓ Nominal current: 2 / 3.45 A
- ✓ Number of pole pairs: 2
- ✓ Power factor: 0.8
- ✓ Rotation speed: 1500 rpm
- ✓ Stator resistance: 2.25 Ω
- ✓ Rotor resistance: 0.7 Ω
- ✓ Cyclic stator inductance: 0.1232 H
- ✓ Cyclic rotor inductance: 0.1112 H
- ✓ Mutual inductance: 0.1118H
- ✓ Moment of inertia of the rotor: 0.05 kg.m²
- ✓ Rated resistive torque: 5 N.m

II.2.5 Caractéristique C= f(Id)

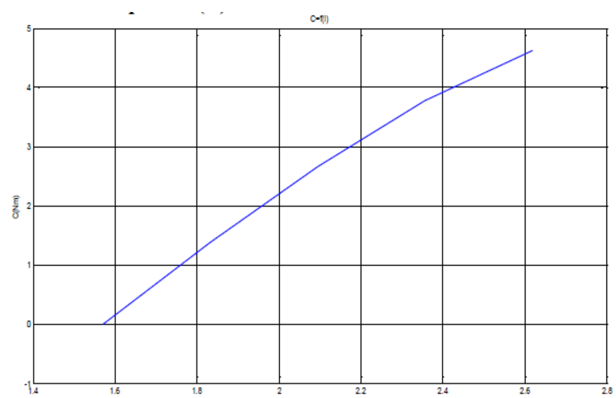


Figure II.3: Electrodynamic characteristic of the hyposynchronous cascade C = f (Is)

The curve of the electrodynamic characteristic C = f (Id) is almost a straight line which returns us to the deduced equation (3.18), i.e. the current follows a shape of a direct current machine .

II.2.6 Caractéristique C= f (g)

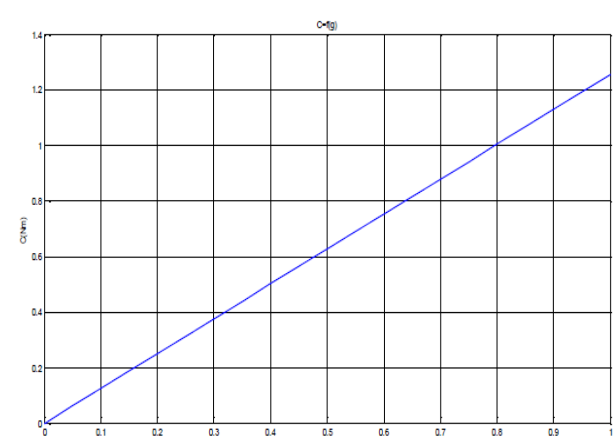


Figure II.4: Characteristic C = f (g) of the hyposynchronous cascade

The characteristic C = f (g) (inverse of the characteristic C = f (Ω)), is proportional to the slip because 0 <g <1, i.e. the torque is inversely proportional to the speed, and for each value of the starting angle α, the machine takes on a well-determined characteristic.

III. MODELISATION DE LA COMMANDE

III.1 Equation d'état de la commande

- The motor was modeled from the voltages that we denote 〚V〛 _an, V_bn and V_cn. The inverter is controlled by logical quantities S_i. We call T_i and T_i 'the transitors (supposed to be ideal switches), we have:
- Si $S_i = 1$, alors $T_i$est passant et $T_{i'}$ est ouvert,
- Si $S_i = 0$, alors $T_i$est ouvert et $T_{i'}$ est passant.

Phase-to-phase voltages are obtained from the outputs of the inverter:

$$\begin{cases} U_{ab} = V_{an0} - V_{bn0} \\ U_{bc} = V_{bn0} - V_{cn0} \\ U_{ca} = V_{cn0} - V_{an0} \end{cases} \qquad (3.1)$$

The phase-to-phase voltages of the load resulting from the phase-to-phase voltages have a zero sum, therefore:

$$\begin{cases} V_{an} = \left(\frac{1}{3}\right)[U_{ab} - U_{ac}] \\ V_{bn=(\frac{1}{3})-[U_{bc}-U_{ab}]} \\ V_{cn} = (\frac{1}{3}) - [U_{ca} - U_{bc}] \end{cases} \qquad (3.2)$$

From the output voltages of the inverter by introducing the neutral voltage of the load with respect to the reference point^{n_0}

$$\begin{cases} V_{an0} = V_{an} + V_{nn0} \\ V_{bn0} = V_{bn} + V_{nn0} \\ V_{cn0} = V_{cn0} + V_{nn0} \end{cases} \qquad (3.3)$$

So we can deduce that:

$$V_{nn0} = \frac{1}{3}[V_{an0} + V_{bn0} + V_{cn0}] \quad (3.4)$$

The state of switches assumed to be perfect

$\Leftrightarrow S_i(i = a, b, c)$ on a :

$$V_{in0} = S_i.U_{dc} - \frac{U_{dc}}{2} = (S_i - 0{,}5)U_{dc} \quad (3.4)$$

On a donc :

$$\begin{cases} V_{an0} = (S_a - 0{,}5)U_{dc} \\ V_{bn0} = (S_b - 0{,}5)\ U_{dc} \\ V_{cn0} = (S_c - 0{,}5)U_{dc} \end{cases} \qquad (3.5)$$

By replacing equation (3.5) in equation (3.4), we get:

$$\begin{cases} V_{an} = \frac{2}{3}V_{an0} - \frac{1}{3}V_{bn0} - \frac{1}{3}V_{cn0} \\ V_{bn} = -\frac{1}{3}V_{an0} - \frac{2}{3}V_{bn0} - \frac{1}{3}V_{cn0} \\ V_{an} = -\frac{1}{3}V_{an0} - \frac{1}{3}V_{bn0} + \frac{2}{3}V_{cn0} \end{cases} \qquad (3.6)$$

By replacing equation (3.5) in equation (3.6), we get:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3}.U_{dc}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} (3.7)$$

Just apply the Park transformation to switch from a three-phase system to a two-phase system.

III.1.1 Commande par modulation sinus-triangle

Sine-triangle PWM (Pulse Width Modulation) is achieved by comparing a low frequency modular wave (reference voltage) to a triangular shaped high frequency carrier wave.

The switching times are determined by the intercession points between the carrier and the modulant. The switching frequency of the switches is set by the carrier. The sinusoidal reference voltages are expressed by :

$$\begin{cases} V_{ref\ a} = V_m \sin(2\pi f t) \\ V_{ref\ b} = V_m \sin(2\pi f t - \frac{2\pi}{3}) \\ V_{ref\ c} = V_m \sin(2\pi f t + \frac{2\pi}{3}) \end{cases} \qquad (3.8)$$

The carrier equation is given by:

$$V_p(t) = \begin{cases} V_{pm}\left[4\left({}^{t}/_{T_p}\right)-1\right] & Si\ 0 \le t \le T_p/2 \\ V_{pm}\left[-4\left({}^{t}/_{T_p}\right)+3\right] & si\ T_p/2 \le t \le T_p \end{cases} \quad (3.9)$$

Où : $T_p = \frac{1}{f_p}$ (3.10)

f : Reference voltage frequency (Hz).

T_p: Carrier period (s).

V_m : Reference voltage amplitude (V).

V_{ref} : Reference voltage (V).

V_{pm} : Peak value of the modulation wave (V)

III.1.2Décomposition en série de Fourier

If f is a periodic function of period T, is integrable, we can decompose it into Fourier series as follows:

$$f(x) = a_0 + \sum_{k=1}^{\infty}(a_k coskx + b_k sinkx) \quad (3.11)$$

Such as :

$$a_0 = \frac{1}{2T}\int_{-T}^{+T} f(x)dx \quad (3.12)$$

$$a_k = \frac{1}{2T}\int_{-T}^{+T} f(x)coskxdx \quad (3.13)$$

$$b_k = \frac{1}{2T}\int_{-T}^{+T} f(x)sinkxdx \quad (3.14)$$

The function f can also be written differently:

$$f(x) = a_0 + \sum_{k=1}^{\infty} A_k sin(kx + \varphi_k) \quad (3.15)$$

Où :

$$A_k = \sqrt{\frac{{a_k}^2 + {b_k}^2}{2}} \quad (3.16)$$

$$\varphi_k = artg\left(\frac{b_k}{a_k}\right) \quad (3.17)$$

III.2 Command simulation

III.2.1 Full wave control

There are six sequences per period. Each electronic switch K_i is closed for half a period (180°). The conduction sequences (command) are:(K_5,K_6,K_1); (K_6,K_1,K_2); (K_1,K_2,K_3); (K_2,K_3,K_1); (K_3,K_4,K_5); (K_4,K_5,K_6). Generally the diodes (called recovery) have the role of returning the negative current emanating from the load towards the source. The capacitor C inserted at the input of the source has the role of filtering the voltage Es and ensuring the reactive energy for the installation of the flux in the air gap of the machine. In the balanced system:

$$\begin{cases} v_a + v_b + v_c = 0 \\ i_a + i_b + i_c = 0 \end{cases} \quad (3.18)$$

$$\begin{cases} U_{ab} = v_a - v_b \\ U_{ac} = v_a - v_c \end{cases} \quad (3.19)$$

From the two equations (3.18) and (3.19), we obtain:

$$\begin{cases} v_a = \dfrac{U_{ab} + U_{ac}}{3} \\ v_b = \dfrac{U_{bc} + U_{ba}}{3} \\ v_c = \dfrac{U_{ca} + U_{cb}}{3} \end{cases} \quad (3.20)$$

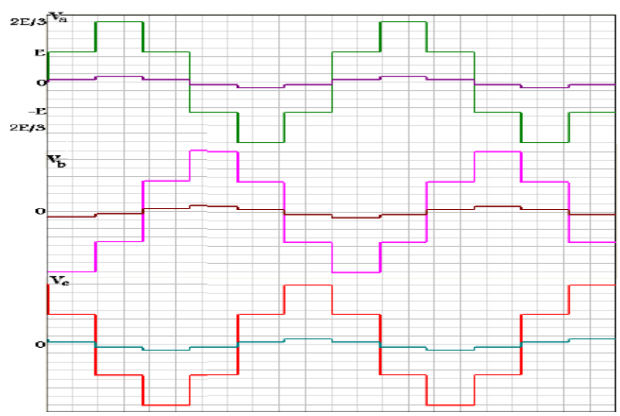


Figure III.1: Currents and voltages delivered by a three-phase inverter output on loads R

III.2.2 PWM control

It is very useful for controlling the asynchronous motor, based on the comparison between two signals, the first is triangular and the second is sinusoidal, the pulse sequences are generated.

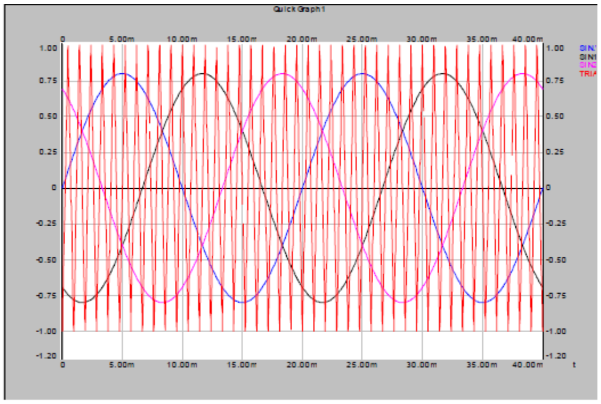


Figure III.2: MLI command strategy

For this control strategy and for a frequency of f = 50 Hz, we define the amplitude ratio and the frequency ratio.

$$r = \frac{U_c}{U_m} \qquad (3.21)$$

$$m = \frac{f_c}{f_m} \qquad (3.22)$$

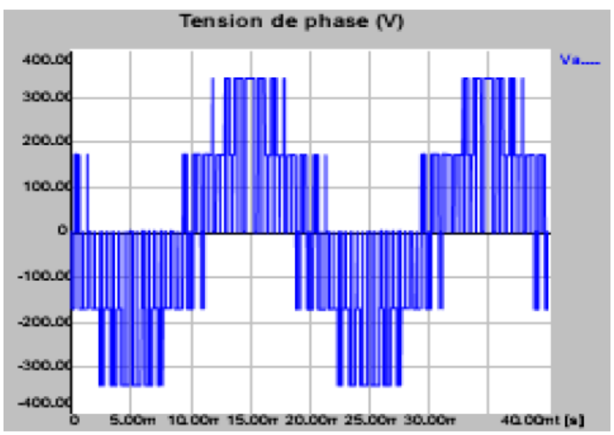


Figure III.3: Phase-to-neutral voltage obtained for a PWM control

IV. MODELING THE VOLTAGE INVERTER

IV.1 Mathematical model

The inverter is a static converter capable of transforming electrical energy from a DC voltage source into AC type electrical energy, the use of inverters is very wide in industry, such as variable speed drives for three-phase motors, emergency power supplies, etc. Thanks to the technological development of semiconductors, and the appearance of new control techniques, inverters have become more efficient.

On the other hand, the output voltage form of an inverter must be closer to a sinusoid for which the harmonic rate is as low as possible, the latter largely depends on the control technique used.

IV.1.1 Fourier series development

The voltage u (t) is an odd square wave function of zero mean value. Its Fourier series decomposition does not contain cosine terms and does not present harmonics of even rank**.**

$$u(t) = \sum_{k=0}^{\infty} \frac{4E_s}{(2K+1)\pi} sin(2K+1)\omega t \qquad (4.1)$$

IV.1.2 Full wave control

There are six sequences per period. Each electronic switch K_i is closed for half a period (180°). Conduction sequences(commande) sont : (K_5,K_6,K_1); (K_6,K_1,K_2); (K_1,K_2,K_3); (K_2,K_3,K_1); (K_3,K_4,K_5); (K_4,K_5,K_6).

Generally the diodes (called recovery) have the role of returning the negative current emanating from the load towards the source. The capacitor C inserted at the input of the source has the role of filtering the voltage Es and ensuring the reactive energy for the installation of the flux in the air gap of the machine. In the balanced system:

$$\begin{cases} v_a + v_b + v_c = 0 \\ i_a + i_b + i_c = 0 \end{cases} \qquad (4.2)$$

$$\begin{cases} U_{ab} = v_a - v_b \\ U_{ac} = v_a - v_c \end{cases} \qquad (4.3)$$

From the two equations (4.21) and (4.22), we obtain:

$$\begin{cases} v_a = \dfrac{U_{ab} + U_{ac}}{3} \\ v_b = \dfrac{U_{bc} + U_{ba}}{3} \\ v_c = \dfrac{U_{ca} + U_{cb}}{3} \end{cases} \qquad (4.23)$$

IV.1.3 PWM control

It is very useful for controlling the asynchronous motor, based on the comparison between two signals, the first is triangular and the second is sinusoidal, the pulse sequences are generated.

For this control strategy and for a frequency of f = 50 Hz, we define the amplitude ratio and the frequency ratio.

$$r = \frac{U_c}{U_m} \qquad (4.24)$$

$$m = \frac{f_c}{f_m} \qquad (4.25)$$

IV.2 SIMULATION

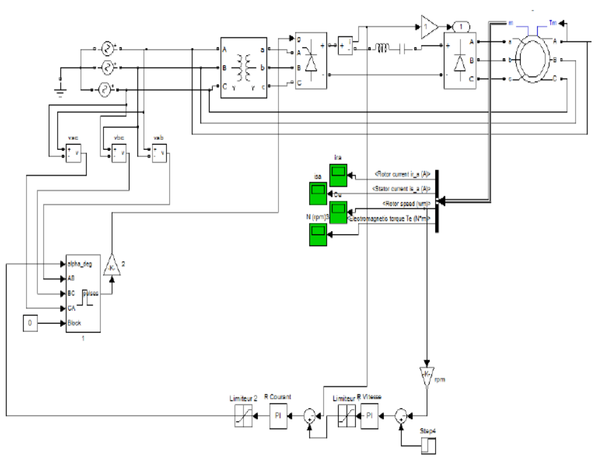
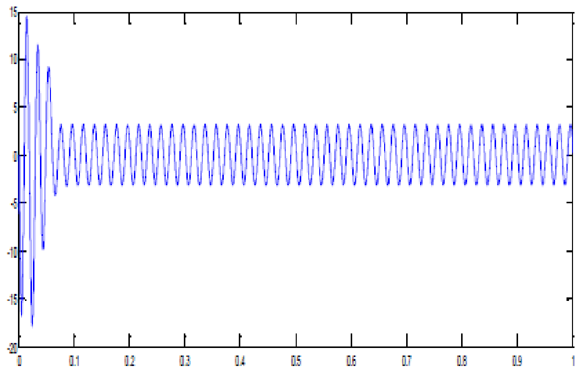


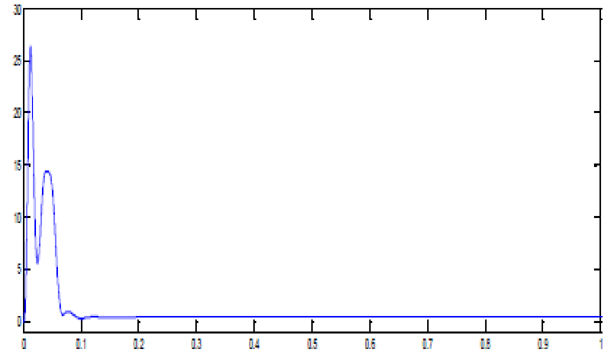
Figure IV.1 :Simulink de commande MLI

IV.3 Simulation and interpretation of the results to be completed

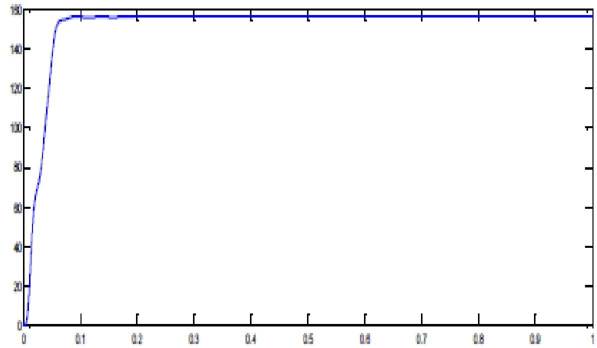
The simulation results given in figure. IV.1, represent the evolution of the fundamental quantities of the asynchronous machine: phase currents, torque, motor speed and electromagnetic torque.



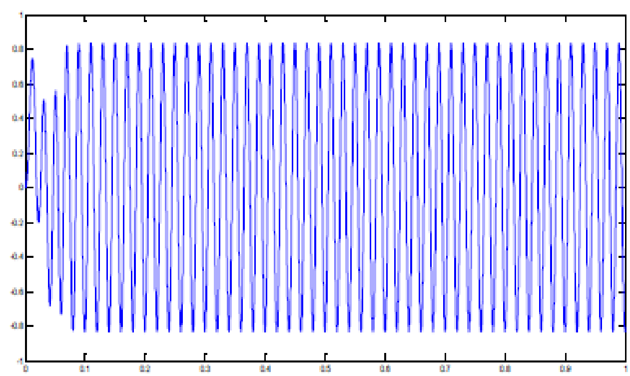
IV.2: Behavior of the stator current



IV.3: Behavior of the couple



IV.3: Speed behavior



IV.4: Comportement de flux

V. CONCLUSION

In this article, we have demonstrated with detailed mathematical models that the rectifier-inverter cascade control is used to control the asynchronous motor with variable speed, i.e. at a frequency independent of the frequency of the network supplying the machine (inverter autonomous).

In this article, we presented the modeling and simulation of the asynchronous motor control. From the simulation results, it can be seen that for the control of the asynchronous machine, control methods are used which make the natural decoupling between the current and the flow, reducing the control of the machine to a control of a machine with direct current, which is shown by equation that the shape of the torque as a function of the current is similar to that of the direct current machine by the software software simulink under the Matlab environment.

This article to present the models of the modeling of a full wave voltage inverter (control at 180 ° and 120 °) and at PWM, the simulation results show that the power supply of the asynchronous machine by a voltage inverter at Pulse-width modulation with a triangular carrier at no-load or on-load, is quite satisfactory as can be seen from the speed characteristic where the ripples are insignificant in steady state as well as the pulsating torques which can be reduced with the increase in modulation index m as it is shown on the characteristic of the couple.

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