FUZZY LOGIC CONTROL OF INDUCTION MOTOR WITH INPUT OUTPUT FEEDBACK LINEARIZATION

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SUMMARY

The proposed system combines the input-output linearization technique and the advantages of fuzzy logic control (intuitiveness, simplicity, easy implementation and minimal knowledge of system dynamics) to obtain a robust, fast and precise control of induction motor speed. The input-output linearizing controller decouples the flux control from the speed control and makes the synthesis of linear controllers possible. However, in practice, parameter variations limit the evolution of the machine flux and the rotor speed. So, a speed fuzzy logic controller for induction motor via feedback linearization with input-output decoupling is presented here in order to achieve better tracking performances. The signal rotor flux is estimated with a nonlinear observer and controlled by classical regulator. Simulation results show the importance of the inclusion of fuzzy logic in designing input-output linearizing control laws. Similarly, it validates the robustness and effectiveness of the proposed fuzzy logic controller for high performance of input-output linearized induction motor drive.

Keywords: *Induction Motor (IM), Input-Output Linearization (IOL), Fuzzy Logic Controller (FLC), and Nonlinear Observer (NLO).*

1. INDRODUCTION

Recently, due to the rapid improvements in power electronics and microprocessors, the field oriented control or the feedback linearization techniques have made the application of the IM drives for high performance applications possible [1,2,3]. In the field oriented method, the decoupling relationship is obtained by the means of proper selection of the state coordinates, under the simplifying hypothesis that the rotor flux is kept constant. Therefore, the rotor speed is only asymptotically decoupled from the rotor flux [4]. The IOL method used the differential geometric approach to design a full linearizing state feedback controller for the IM [5]. The decoupling condition always holds, but the parameters of the IM must be precisely known and accurate information on the rotor flux is required. Some rotor flux observer were proposed to estimate the rotor flux [6,7]. The parameter uncertainty in the IM is owing mainly to the thermal variation and the load torque change which are slowly varying in general. Adaptive controller is very suitable for this kind of system. The design of classical adaptive control system is based on mathematical modelling and the implementation of such system is usually complex due to the computationally intensive algorithms [8,9]. However, in the robust control methods, fuzzy logic control technique, has been successfully applied to the control of motor drives in recent years [10]. FLC is implemented using fuzzy reasoning which is simpler since it does not need complicated mathematical manipulation. In the proposed system, FLC is used to drive the speed rotor. It requires expertise knowledge of the system for FLC parameter setting, and the controller can be only as good as the expertise is involved in the design. In this control strategy it is assumed that all the states are measured. In fact, a part of the states, the rotor fluxes are not easily measurable. A NLO is used to provide estimates of the rotor flux states.
This paper presents a theoretical study of speed FLC for IM drives using IOL technique in order to decompose the motor model into two separate subsystems, rotor speed and rotor flux amplitude.

This work is organised as: Section 2, the nonlinear mathematical model is first presented. Section 3 describes IOL technique and is application to IM. Section 4 develops the suggested design of FLC. In section 5, is presented the detailed analysis of nonlinear observer for rotor flux. In section 6, simulation results are given to demonstrate the advantages of the proposed scheme. Various tests of Speed FLC scheme under different motor operation conditions are presented to show the control properties. Finally, conclusion and further studies are explained in the last section.

2. NONLINEAR INDUCTION MOTOR MODEL

In order to reduce the complexity of the three phase model, an equivalent two phase representation is chosen. Nonlinear control allows controlling the model in a stator fixed reference frame avoiding the transformation in rotation reference frame [11]. Under the assumptions of linearity of the magnetic circuit and neglecting iron losses, a three phase IM model in the fixed stator α,β reference frame can be described as [12]:

$$\dot{x} = f(x) + gu = f(x) + g_1 u_{\alpha s} + g_2 u_{\beta s} \tag{1}$$

Where: $u_s = (u_{\alpha s} \;\; u_{\beta s})^T$ stator voltage,
$\phi_r = (\phi_{\alpha r} \;\; \phi_{\beta r})^T$: rotor flux,
$i_s = (i_{\alpha s} \;\; i_{\beta s})^T$: stator current, Ω : mechanical speed,

$$f(x) = \begin{bmatrix} -\nu i_{\alpha s} + \frac{K}{T_r}\phi_{\alpha r} + p\Omega K \phi_{\beta r} \\ -\nu i_{\beta s} - p\Omega K \phi_{\alpha r} + \frac{K}{T_r}\phi_{\beta r} \\ \frac{M}{T_r} i_{\alpha s} - \frac{1}{T_r}\phi_{\alpha r} - p\Omega \phi_{\beta r} \\ \frac{M}{T_r} i_{\beta s} + p\Omega \phi_{\alpha r} - \frac{1}{T_r}\phi_{\beta r} \end{bmatrix}$$

$$g_1 = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 \end{bmatrix}^T, \; g_2 = \begin{bmatrix} 0 & \frac{1}{\sigma L_s} & 0 & 0 \end{bmatrix}^T$$

$$\sigma = 1 - \frac{M^2}{L_r L_s}, \; \nu = \frac{R_s}{\sigma L_s} + \frac{R_r M^2}{\sigma L_s L_r^2},$$

$$K = \frac{M}{\sigma L_s L_r}, \; T_r = \frac{L_r}{R_r}, \quad g = (g_1 \quad g_2)^T$$

We want to control the electromagnetic torque T_e and the square rotor flux $\phi_r^{\,2}$. Then, the output equation is:

$$y(x) = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} = \begin{bmatrix} p\frac{M}{L_r}(\phi_{\alpha r} i_{\beta s} + \phi_{\beta r} i_{\alpha s}) \\ \phi_{\alpha r}^2 + \phi_{\beta r}^2 \end{bmatrix} \tag{2}$$

Where T_e : Electromagnetic torque,
T_L : Load torque
The parameters of the considered motor are given in appendix B.

3. IOL TECHNIQUE

The IOL technique is based on exact cancellation of the system's nonlinearities in order to obtain a linear relationship between the control inputs and the system outputs in the closed loop. The nonlinear control law is reduced to a successive differentiation of each output until at least one input appears in the derivative. The following notation will be used for the directional or Lie derivative of the output function $h(x)$: $R^n \to R$ along a vector field $f(x) = [f_1(x), \ldots\ldots\ldots, f_n(x)]^T$

$$L_f h(x) = \sum_{i=1}^{n} \frac{\partial h(x)}{\partial x_i} f_i(x) \tag{3}$$

Thus the derivatives of the outputs are given by

$$\begin{aligned} \dot{h}_1(x) &= L_f h_1(x) + L_{g_1} h_1(x) u_{\alpha s} + L_{g_2} h_1(x) u_{\beta s} \\ \dot{h}_2(x) &= L_f h_2(x) \\ \ddot{h}_2(x) &= L_f^2 h_2(x) + L_{g_1} L_f h_2(x) u_{\alpha s} + L_{g_2} L_f h_2(x) u_{\beta s} \end{aligned} \tag{4}$$

Lie derivative expressions are given in appendix B

In the next step the IOL of the nominal system is performed. The nominal part of the IM model is written in the form of higher derivatives of inputs.

$$\begin{bmatrix} \dot{h}_1(x) \\ \ddot{h}_2(x) \end{bmatrix} = \begin{bmatrix} L_f h_1(x) \\ L_f^2 h_2(x) \end{bmatrix} + D(x) \begin{bmatrix} u_{\alpha s} \\ u_{\beta s} \end{bmatrix} \tag{5}$$

Where $D(x) = \begin{bmatrix} L_{g_1} h_1(x) & L_{g_2} h_1(x) \\ L_{g_1} L_f h_2(x) & L_{g_1} L_f h_2(x) \end{bmatrix}$

is the decoupling matrix. D(x) is non singular, except at the motor start up, where $\phi_r = 0$ $[\det D(x) = -2pK^2 R_r(\phi_{\alpha r}^2 + \phi_{\beta r}^2)]$. The linearized and decoupled IM model is obtained by an appropriate selection of the control input $u = \begin{bmatrix} u_{\alpha s} & u_{\beta s} \end{bmatrix}^T$ in the form

$$\begin{bmatrix} u_{\alpha s} \\ u_{\beta s} \end{bmatrix} = D^{-1}(x) \begin{bmatrix} -L_f h_1(x) + v_1 \\ -L_f^2 h_2(x) + v_2 \end{bmatrix} \tag{6}$$

Note that $v = \begin{bmatrix} v_1 & v_2 \end{bmatrix}^T$ is the new system inputs. The resulting closed loop system is governed by the equation (7)

$$\begin{aligned} \dot{h}_1(x) &= v_1 \\ \ddot{h}_2(x) &= v_2 \end{aligned} \tag{7}$$

The new input signal 'v' is chosen following simple linear pole placement technique to guarantee stability.

$$\begin{aligned} v_1 &= -k_{p1}(T - T_{ref}) + \dot{T}_{ref} \\ v_2 &= -k_{p2}(\phi_r^2 - \phi_{r\,ref}^2) - k_{d2}(\dot{\phi}_r^2 - \dot{\phi}_{r\,ref}^2) + \ddot{\phi}_{r\,ref}^2 \end{aligned} \tag{8}$$

Where T_{ref} and $\phi_{r\,ref}^2$ are torque and flux references. Note that the references for torque and flux have to be once or twice differentiated. Thus we implemented a second order state variable filter for the flux where the states give the flux reference and their derivatives. Since we want to control speed we implement a FLC which gives the reference torque and compensate variations of the load torque.

4. FLC DESIGN

The fuzzy controller is used to perform nonlinear decoupling control in order to obtain better responses under parameter variations [13].

4.1. Fundamentals of FLC

The schematic diagram of a FLC for IM drive is shown in fig.1

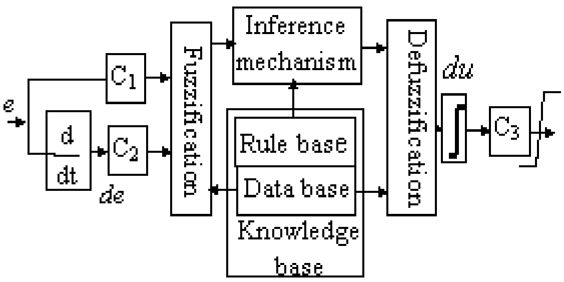

Fig. 1 Internal FLC structure

The FLC has three functional blocks for calculation and knowledge base which contains two databases. The functional blocks in FLC are

1. Fuzzification

Fuzzification is defined as the mapping from a real valued point to fuzzy set. In most fuzzy decision systems, non fuzzy input data is mapped to fuzzy sets by treating them as triangular membership functions, gaussian membership functions, ...

2. Inference mechanism

Fuzzy inference is used to combine the fuzzy IF-THEN in the fuzzy rule base, and to convert input information into output membership functions. An inference mechanism emulates the expert's decision making in interpreting and applying knowledge about how to perform good control. The rule may use the experts experience and control engineering knowledge. There are three types fuzzy rule based models for function approximation. Mandani model, Takagi-sugeno model,and Kosko's addition model.

3. Defuzzification

There are many methods which can be used for converting the conclusions of the inference mechanism into the actual input for the plant. Centre of gravity defuzzification method is often used [13]. Other defuzzification strategies can be found in technique literatures.

4.2. Design of FLC

The inputs to the fuzzy controller are error (e) and variation error (de). The output of the fuzzy controller is (du). The universe of (e), (de), and (du) are partitioned into three fuzzy sets. NB (Negative Big), EZ (Equal Zero), and PB (Positive Big). Each fuzzy set is represented by triangular membership function or trapezoidal membership function (see fig.2 (a)). The rule base of the FLC contains nine rules based on the IF-THEN structure which are tabulated in table1. The crisp output of the FLC is obtained by using Max-Min inference algorithm and the centre of gravity defuzzification approach. It is known that the sensitivity and performance of FLC system are significantly affected by the weighting factors C_1, C_2, and C_3. However, we lack a general methodology for choosing these factors. In this paper, a trial and error approach is used to determine and adjust these weighting factors [13]. The control surface fig.2 (b) represented by a three dimensional graphic showing the output variable corresponding to all combinations of values of the inputs can be used to facilitate the FLC tuning.

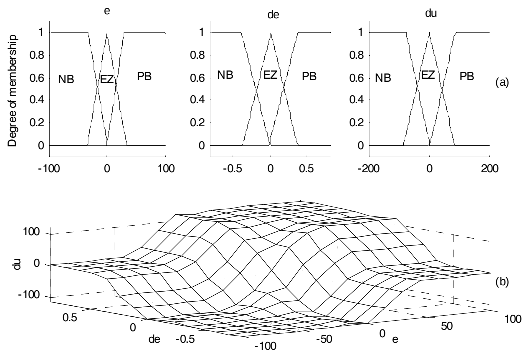

Fig. 2 Membership functions (a) and input-output map (b)

du		e		
		NB	EZ	PB
de	NB	NB	NB	EZ
	EZ	NB	EZ	PB
	PB	EZ	PB	PB

Tab.1 Mamdani Rules

5. NONLINEAR OBSERVER

Variable speed AC drives based on IOL control require an evaluation of the instantaneous magnetic flux of the rotor. Here, a NLO [12] is used to construct the unknown states of the rotor flux. This observer is given by

$$\dot{\hat{x}}=\begin{bmatrix}-\nu & 0 & \frac{K}{T_t} & p\Omega K\\ 0 & -\nu & -p\Omega K & \frac{K}{T_t}\\ \frac{M}{T_r} & 0 & -\frac{1}{T_t} & -p\Omega\\ 0 & \frac{M}{T_r} & p\Omega & -\frac{1}{T_r}\end{bmatrix}\hat{x}+gu+\begin{bmatrix}-k_1 & 0\\ 0 & -k_1\\ -\frac{k_2}{T_r} & p\Omega k_2\\ -p\Omega k_2 & -\frac{k_2}{T_r}\end{bmatrix}\hat{u}_s+\begin{bmatrix}f_{\alpha i}\\ f_{\beta i}\\ 0\\ 0\end{bmatrix} \quad (9)$$

$\hat{x}=(\hat{i}_s^T\ \hat{\phi}_r^T)^T$: the estimated state, $f_{\alpha i}\ f_{\beta i}$ are defined by the whole stability system in [12] with

$$k_1=2\theta$$
$$k_2=\frac{T_r^2\theta^2}{K[1+(p\Omega T_r)^2]}$$

This leads to the following error equation $\tilde{x}=x-\hat{x}$

$$\dot{\tilde{x}}=\begin{bmatrix}-\nu-k_1 & 0 & \frac{K}{T_t} & p\Omega K\\ 0 & -\nu-k_1 & -p\Omega K & \frac{K}{T_t}\\ \frac{M}{T_r}-\frac{k_2}{T_t} & p\Omega k_2 & -\frac{1}{T_t} & -p\Omega\\ -p\Omega k_2 & \frac{M}{T_r}-\frac{k_2}{T_r} & p\Omega & -\frac{1}{T_r}\end{bmatrix}\tilde{x}-\begin{bmatrix}f_{\alpha i}\\ f_{\beta i}\\ 0\\ 0\end{bmatrix} \quad (10)$$

The two controlled outputs of the system are unknown, so, we define the estimated outputs

$$\begin{bmatrix}\hat{h}_1(x)\\ \hat{h}_2(x)\end{bmatrix}=\begin{bmatrix}p\frac{M}{L_r}(\hat{\phi}_{\alpha r}\hat{i}_{\beta s}+\hat{\phi}_{\beta r}\hat{i}_{\alpha r})\\ \hat{\phi}_{\alpha r}^2+\hat{\phi}_{\beta r}^2\end{bmatrix} \quad (11)$$

The derivatives of $\hat{h}_1$ and $\hat{h}_2$ are defined as:

$$\begin{aligned}\dot{\hat{h}}_1&=L_{\hat{f}}\hat{h}_1+L_{g_1}\hat{h}_1u_{\alpha s}+L_{g_2}\hat{h}_1u_{\beta s}\\ \dot{\hat{h}}_2&=L_{\hat{f}}\hat{h}_2\end{aligned} \quad (12)$$

As $L_f\hat{h}_2$ is not function of the control inputs, we should derive once again. But $L_f\hat{h}_2$ contains terms function of currents, differentiating these terms introduces terms of flux which are unknown. To over this problem, his can be written as[12]:

$$L_f\hat{h}_2=-\frac{2}{T_r}\hat{h}_2+\hat{h}_3+\Delta \quad (13)$$

Where

$$\hat{h}_3=\frac{2M}{T_t}(\hat{i}_{\alpha s}\hat{\phi}_{\alpha r}+\hat{i}_{\beta s}\hat{\phi}_{\beta r})$$
$$\Delta=2(\frac{k_2}{T_r}\hat{\phi}_{\alpha r}+p\Omega\hat{\phi}_{\beta r})\hat{i}_{\alpha s}+2(\frac{k_2}{T_r}\hat{\phi}_{\beta r}-p\Omega\hat{\phi}_{\alpha r})\hat{i}_{\beta s}$$

$\hat{h}_3$ is an artificial auxiliary output [12].

Let us differentiate $\hat{h}_3$

$$\dot{\hat{h}}_3=L_{\hat{f}}\hat{h}_3+L_{g_1}\hat{h}_3u_{\alpha s}+L_{g_2}\hat{h}_3u_{\beta s} \quad (14)$$

This leads, in fine, to:

$$\begin{bmatrix}\dot{\hat{h}}_1\\ \dot{\hat{h}}_2\\ \dot{\hat{h}}_3\end{bmatrix}=\begin{bmatrix}L_{\hat{f}}\hat{h}_1+L_{g_1}\hat{h}_1u_{\alpha s}+L_{g_2}\hat{h}_1u_{\beta s}\\ -\frac{2}{T_r}\hat{h}_2+\hat{h}_3+\Delta\\ L_{\hat{f}}\hat{h}_3+L_{g_1}\hat{h}_3u_{\alpha s}+L_{g_2}\hat{h}_3u_{\beta s}\end{bmatrix} \quad (15)$$

The Lie derivative estimates are given in appendix C

The error between the desired trajectory of the outputs and the estimate outputs are

$$\begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix}=\begin{bmatrix}\hat{h}_1-h_{1ref}\\ \hat{h}_2-h_{2ref}\\ \hat{h}_3-h_{3ref}\end{bmatrix} \quad (16)$$

Let us design the control inputs as:

$$\begin{bmatrix}u_{\alpha s}\\ u_{\beta s}\end{bmatrix}=\begin{bmatrix}L_{g_1}\hat{h}_1 & L_{g_2}\hat{h}_1\\ L_{g_1}\hat{h}_3 & L_{g_2}\hat{h}_3\end{bmatrix}^{-1}*\begin{bmatrix}-L_{\hat{f}}\hat{h}_1-k_{p_1}e_1+\dot{h}_{1ref}\\ -L_{\hat{f}}\hat{h}_3-e_2-k_{p_3}e_3+\dot{h}_{3ref}\end{bmatrix} \quad (17)$$

This leads to:

$$\begin{bmatrix}\dot{e}_1\\ \dot{e}_2\\ \dot{e}_3\end{bmatrix}=\begin{bmatrix}-k_{p_1}e_1\\ -\frac{2}{T_r}\hat{h}_2+\hat{h}_3+\Delta-\dot{\hat{h}}_{2ref}\\ -e_2-k_{p_3}e_3\end{bmatrix} \quad (18)$$

Taking h_{3ref} as :

$$h_{3ref}=\frac{2}{T_r}\hat{h}_2+\dot{h}_{2ref}-k_{p2}e_2 \quad (19)$$

Leads to (Δ is set to zero)

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} -k_{p_1} & 0 & 0 \\ 0 & -k_{p_2} & 1 \\ 0 & -1 & -k_{p_3} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} \tag{20}$$

A simple linear study would be sufficient to establish the stability of (20).

6. SIMULATION RESULTS

The proposed FLC for controlling the speed of IM with IOL decoupling and flux NLO was designed for 1.1kw drive is represented in fig.3.

The performance was verified by means of simulations. Parameter values of the IM are given in the appendix A. In order to valid the algorithm for a large operating domain, we use the reference profiles shown on figure.4

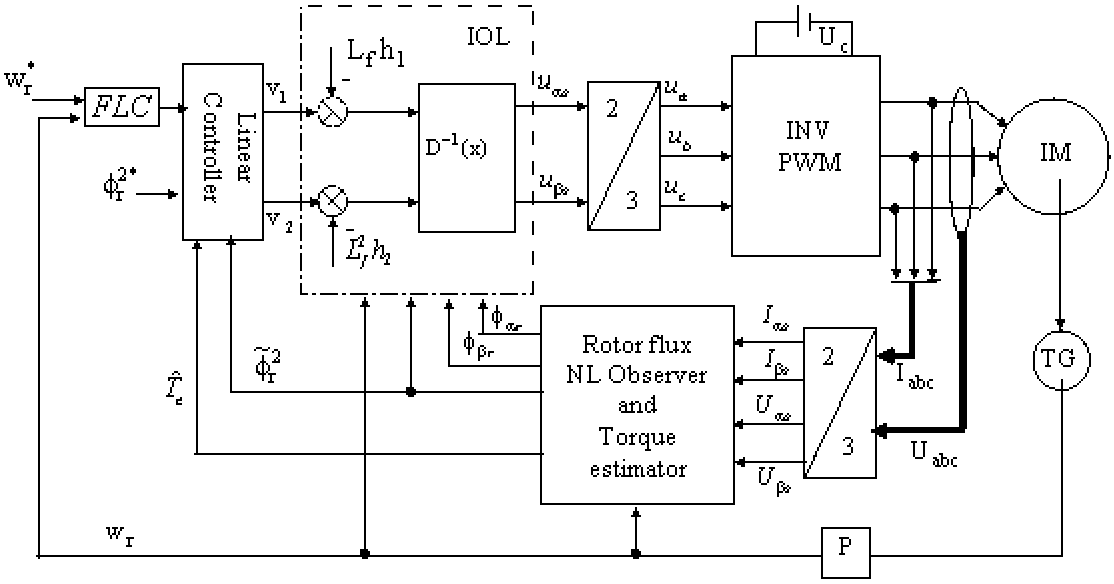

Fig. 3 Speed FLC for IM decoupled with IOL

Fig.5 shows in increasing regime or decreasing regime, the rotor speed tracks the reference speed with smooth constant delay. In constant regime, the rotor speed follows exactly the reference speed. At the abrupt variations of the speed or the load torque a transient pick appears in the speed error which shows the reaction of the corrector in the speed response.

Fig.6 shows that the electromagnetic torque follows the load torque when the speed is constant. During an increase or decrease of the speed the electromagnetic torque tracks the load torque with an augmented torque corresponding to accelerator or decelerator torque.

The performance of the drive is tested for parameter variation, which is shown in fig.7 the inertia is doubled. It shown from this figure that the proposed drive can fellow the command speed almost accurately due to the robustness of the FLC.

From fig.8 we remark a good tracking in flux regulation and flux observation.

Fig.9 shows that the decoupling between the axis ‘d’ and ‘q’ is maintained under load (see speed error) and speed variations by the input-output linearization technique. So, the observed flux or rotor flux, after a short transient regime in start up fellows only the reference flux and is independent of the speed and torque variations.

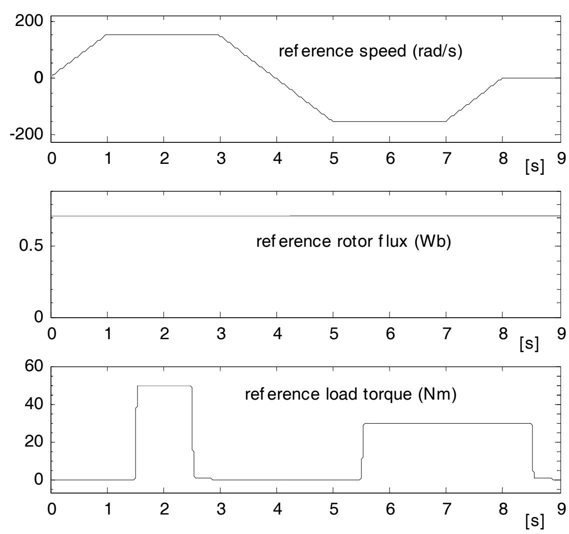

Fig. 4 Reference trajectories

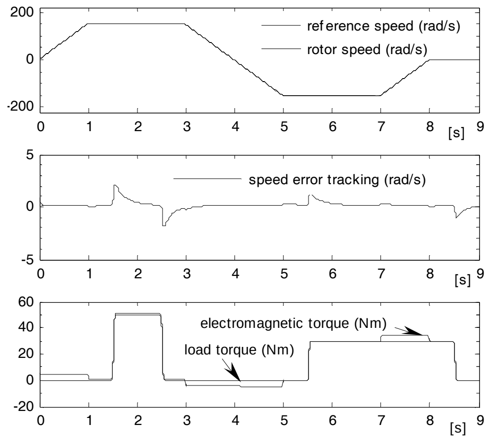

Fig. 5 Speed variations under nominal inertia and load variations

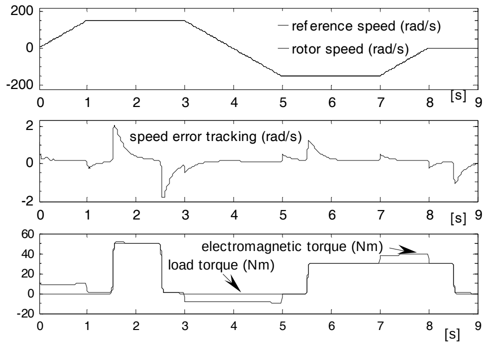

Fig. 6 Speed variations under double inertia and load variations

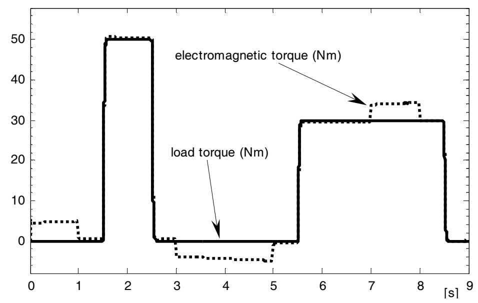

Fig. 7 Electromagnetic torque and load torque

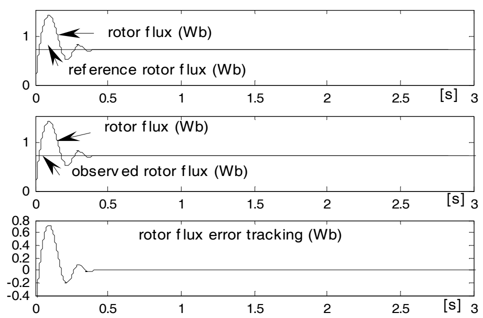

Fig. 8 Zoom of flux responses

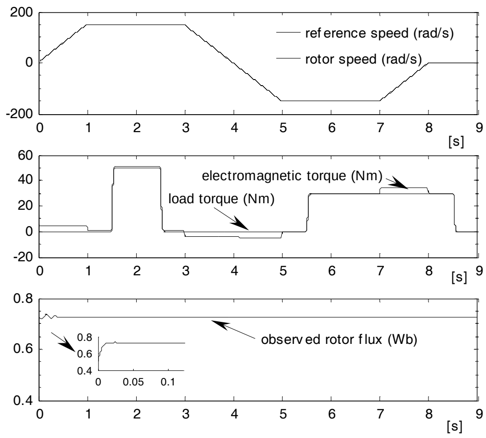

Fig. 9 Speed variations with constant flux

7. CONCLUSION

The different results obtained show that the developed FLC used with NLC method gives very good performances for the induction motor control. The decoupling between the rotor flux and rotor speed is maintained under load and speed variations (fig.9).The advantages of the proposed NLO may be resumed as follows: high convergence rate of the rotor flux components estimation and computational time in the choice of θ. The combination of the decoupling by nonlinear state feedback and the FLC theory based on linguistic expert control interpretations permits to avoid the problem of flux orientation and inexactitude of the representative system model. This strategy of control gives a stable system with a satisfactory performance either with or without load variations. The performance depends on the operator expertise. The proposed speed FLC has a good robustness and less sensitive to parameter variations. The assumption made in the development of this control law is the linearity of the magnetic circuit of the machine. However, there is no guarantee that the magnetic flux remains in the linear magnetic region during machine transients. Then, the problem of controlling the IM with magnetic saturation will be studied in the perspective.

APPENDIX

A. Induction motor parameters

The induction motor used in this drive system is a three-phase, Y-connected, four poles, 1.1Kw, 60Hz, 220V/2.6A type. The nominal values of the motor used in this simulation are given in the table below.

Designation	Parameter	Value
Rotor resistance	R	4.3047 Ω
Stator resistance	R	9.65 Ω
Mutual inductance	M	0.4475 H
Stator inductance	L	0.4718 H
Rotor inductance	L	0.4718 H
Rotor inertia	J	0.0293 $kg.m$
Pole pair	P	2
Viscouse frict. Coef	f	0.0038 $Nm.rad.s$
Mechanical power	P	1.1 kw
Nominal voltage	V	220v
Nominal current	I	2.6A
Nominal speed	n	1410 rpm

B. Lie derivative calculation

$$L_f h_1 = p\frac{M}{L_r}\begin{bmatrix} \left(\frac{1}{T_r} + v\right) + \left(\phi_{\alpha r} i_{\beta s} - \phi_{\beta r} i_{\alpha s}\right) + \\ p\Omega\left(\phi_{\alpha r} i_{\alpha s} + \phi_{\beta r} i_{\beta s}\right) + \\ P\Omega K\left(\phi_{\alpha r}^2 + \phi_{\beta r}^2\right) \\ \end{bmatrix}$$

$$L_f h_2 = \frac{2}{T_r}\left[M(\phi_{\alpha r} i_{\alpha s} + \phi_{\beta r} i_{\beta s}) - (\phi_{\alpha r}^2 + \phi_{\beta r}^2)\right]$$

$$\begin{aligned} L_f^2 h_2 = {} & \left(\frac{4}{T_r^2} + \frac{2K}{T_r^2}M\right)(\phi_{\alpha r}^2 + \phi_{\beta r}^2) - \left(\frac{6M}{T_r^2} + \frac{2\nu}{T_r}M\right)(\phi_{\alpha r} i_{\alpha s} + \phi_{\beta r} i_{\beta s}) \\ & + \frac{2Mp\Omega}{T_r}(\phi_{\alpha r} i_{\beta s} - \phi_{\beta r} i_{\alpha s}) + \frac{2}{T_r^2}M^2(i_{\alpha s}^2 + i_{\beta s}^2) \end{aligned}$$

$$L_{g_1} h_1 = -pK\phi_{\beta r} \qquad L_{g_1} L_f h_2 = 2R_r K\phi_{\alpha r}$$

$$L_{g_2} h_1 = pK\phi_{\alpha r} \qquad L_{g_2} L_f h_2 = 2R_r K\phi_{\beta r}$$

C. Lie derivative estimation

$$L_{\hat f}\hat h_1 = p\frac{M}{L_r}(-\hat f_1\hat\phi_{\beta r} + \hat f_2\hat\phi_{\alpha r} + \hat f_3\hat i_{\beta s} - \hat f_1\hat i_{\alpha s})$$

$$L_{\hat f}\hat h_2 = 2\hat f_3\hat\phi_{\alpha r} + 2\hat f_4\hat\phi_{\beta r}$$

$$L_{g_1}\hat h_1 = -p\frac{M}{\sigma L_s L_r}\hat\phi_{\beta r}$$

$$L_{g_2}\hat h_1 = p\frac{M}{\sigma L_s L_r}\hat\phi_{\alpha r}$$

$$\hat f_1 = -\nu\hat i_{\alpha s} + \frac{K}{T_r}\hat\phi_{\alpha r} + p\Omega K\hat\phi_{\beta r} - 2\theta\hat i_{\alpha s} - f_{\alpha i}$$

$$\hat f_2 = -\nu\hat i_{\beta s} + \frac{K}{T_r}\hat\phi_{\beta r} - p\Omega K\hat\phi_{\alpha r} - 2\theta\hat i_{\beta s} - f_{\beta i}$$

$$\hat f_3 = \frac{M}{T_r}\hat i_{\alpha s} - \frac{1}{T_r}\hat\phi_{\alpha r} - p\Omega\hat\phi_{\beta r} - \frac{k_2}{T_r}\hat i_{\alpha s} + p\Omega k_2\hat i_{\beta s}$$

$$\hat f_4 = \frac{M}{T_r}\hat i_{\beta s} - \frac{1}{T_r}\hat\phi_{\beta r} + p\Omega\hat\phi_{\alpha r} - \frac{k_2}{T_r}\hat i_{\beta s} - p\Omega k_2\hat i_{\alpha s}$$

$$L_{\hat f}\hat h_3 = -\frac{2M}{T_r}\hat\phi_{\alpha r}\hat f_1 + \frac{2M}{T_r}\hat\phi_{\beta r}\hat f_2 + \frac{2M}{T_r}\hat i_{\alpha s}\hat f_3 + \frac{2M}{T_r}\hat i_{\beta s}\hat f_4$$

$$L_{g_1}\hat h_3 = -p\frac{M}{\sigma L_s T_r}\hat\phi_{\beta r}$$

$$L_{g_2}\hat h_3 = p\frac{M}{\sigma L_s T_r}\hat\phi_{\alpha r}$$

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