INTELLIGENT CONTROL OF INDUCTION MOTOR USING INTERVAL TYPE-2 FUZZY LOGIC

S. RAFA[1,2] L. BARAZANE A. LARABI
[1]The Industrial Electrical System, University of Science and Technology Houari Boumediene, Algeria
USTHB, BP32 EL ALIA, Phone: + (213)021 207 669, Fax: + (213)021 207 669, Email:souad.rafa@univ-reims.fr

M. MANCEUR N. ESSOUNBOULI A. HAMZAOUI
[2]CReSTIC, IUT of Troyes, University of Reims Champagne Ardenne, France
9 Rue de Québec B.P. 396, Troyes cedex, Phone: +(33) 3 25 42 71 79, Fax: +(33) 3 25 42 70 98.

Abstract: *The aim of this paper consists of presenting a new approach to control an induction motor using type-2 fuzzy logic. The induction motor has a nonlinear model, uncertain and strongly coupled. The vector control technique solves the coupling problem. Unfortunately, in practice this is not checked because of uncertainties in the model. Indeed, the presence of uncertainties led us to use the techniques of fuzzy logic. This technique is used to replace the block of FOC with a new block control its role is to maintain the decoupling and overcome the problem of robustness with respect to the parametric variation. The simulation results show that the two control schemes provide in their basic configuration, comparable performances regarding the decoupling. However, the choice for the type-2 Fuzzy vector control appears advantageous. The type-2 fuzzy vector control is found to be a robust control for application in an induction motor.*

Key words: *Induction Motor, Vector control, Type-2 fuzzy logic, Intelligent control.*

1. INTRODUCTION

The induction motor is widely used in industry, mainly due to the simplicity of its structure, its rigidness, maintenance-free operation, and relatively low cost [1, 2]. In the opposite of the DC motor, this one can be used in aggressive or volatile environments since there are no risks of corrosion or sparks [3]. However, it is still a challenging problem to control induction motors to get the perfect dynamic performance because its model is usually multi-variable, coupled, highly nonlinear, the electric rotor variables are not measurable, and its physical parameters are generally imprecisely known because they are time-varying [3, 4].

Due to power electronics progress, appearance of new fast components, and development of the numerical control technologies, it becomes easy to establish rather complex control making it possible to reach high performances of torque and speed control of an induction motor. In this context, one of the standard controls structures and best adapted to the industrial requirements is that the field oriented control. This technique offers a solution to avoid solving higher order equations with a large number of variables and non-linearity and achieves an efficient control with high dynamic. This approach has the following advantages: the flux and torque are controlled independently, in a similar fashion to a separately excited DC machine [5], full motor torque capability at low speed, better dynamic behavior, higher efficiency for each operating point in a wide speed range, and four quadrant operations. However, this control needs more calculations than other standard control schemes and is penalized by its complexity of structure and its sensitivity to the parameter variations in particular those of the rotor.

To simplify the control structure some approaches based on backstepping have been presented in the literature [6, 7, 8]. It presents the advantages to use only one control loop. For example in [8], the authors propose a backstepping fuzzy adaptive controller, where they use backstepping to control the speed and the current in the same loop. To overcome the assumption on the machine parameters knowledge, an adaptive fuzzy system is exploited to approximate the unknown dynamics, which allows considering the advantages of direct and indirect adaptive schemes. Nevertheless, this structure requires calculation time and measuring currents which increases the implementation costs.

Another approach applies in the control field using sliding mode control to deal to the uncertainties; this approach is powerful to control nonlinear and uncertain systems [9, 10]. However, it is difficult to obtain the bound of lumped uncertainty in advance for practical applications of SMC. Besides, the disadvantage exists in the application of SMC system is the undesired chattering phenomena which raises imperfection for practical switching device using.

During the past decade, intelligent methodologies have been found to possess the best potential to solve many engineer problems which, cannot be solved before. Especially the fuzzy logic has been explored during the past few years by several researchers [11, 12, 13, 14]. The main property that distinguishes fuzzy logic is its capacity of representing and modeling imprecision and uncertainty [15]. The fuzzy systems can be considered as a universal approximator, and hence can approximate any continuous functions on a compact set to a given accuracy [16]. Fuzzy logic based approaches don't require complex mathematical models as used in classic control. The basic principle of fuzzy logic was stated by the use of "linguistic variables" in place of or in addition to numerical variables, the characterization of simple relations between variables by "conditional fuzzy statement" and the characterization of complex relations by "fuzzy algorithms"[13].

The classical fuzzy logic control (called type-1 fuzzy logic control and noted T1FLC) strategy has been the focus of many studies and research for the control of induction motor [17, 18, 19, 20]. One of the advantages of the fuzzy based control is that linguistic information can be directly incorporated into the controller without the need to accurate mathematical model of the system.

However, the imprecision in such classical fuzzy system, which is called sometimes Type-1 fuzzy logic system (T1FLS) is not fully exploited and can deliver a non-satisfactory performance. Practically, three ways of uncertainty can be observed in the fuzzy logic system (FLS): (1) the used words in antecedents and consequents of rules can have different meaning to different people; (2) consequents obtained by polling a group of experts will often be different from the same rule; and (3) both of training data and measurements used to activate the FLS are noisy [21, 22]. Despite having a name which carries the connotation of uncertainty, research has shown that there are limitations in the ability of T1FLS to model and minimize the effect of uncertainties [23, 24, 25, 26].

Recently, the applications of type-2 fuzzy logic (T2FL) to uncertain control processes have received considerable attention [24]. This concept was also introduced by Lofti Zadeh in 1975 [25]. Nevertheless, the first T2FL system was developed and presented only 23 years later by N. Karnik and J. Mendel in [28]. As J. Mendel defines, type-2 is an expanded and richer fuzzy logic which, enables to better handle the uncertainty [29]. This technique is a relatively new. Indeed, in the last years it has begun to interest researchers around the world, the number of publications increases at a high rate. Most of the authors working in this research consider that T2FL can outperform their counterparts T1FL because they can model complex processes, it's characterized by MFs that are themselves fuzzy and it is usually more robust and better able to eliminate oscillations. The interval type-2 (IT2) [25], a special case of type-2 FLS, are currently the most widely used for their reduced computational cost.

In this paper, we propose a new approach to control the induction motor by using Interval type-2 Fuzzy Logic, in order to design a fuzzy control capable of encompassing all the uncertainties of the motor and to provide a robust and simple control. Indeed, this control retains ownership of the rotor flux orientation without using park transformation, which allows us to eliminate the PI and current sensors and make its implementation cheaper. For this control, we impose the rotor flux and we use a single loop speed to control the motor, the control voltages and the stator pulsation are deduced from the type-2 fuzzy rules taking account parametric variations.

This control strategy has been performed on a typical induction motor with 1.5 kW rating, with parameter reported in the APPENDIX B. The paper is organized as follows: in section II, a model of induction motor is presented. In section III, the vector control theory is presented. In section IV, we give an overview of the theory of the type-2 fuzzy logic. Section V, the new approach using the type-2 fuzzy logic is presented. In section VI, the simulation results are presented. Finally, concluding remarks are given in section VII.

2. MATHEMATICAL MODEL OF AN INDUCTION MOTOR

A three-phase induction motor with squirrel cage rotor is considered in this paper. Assuming that three-phase AC voltages are balanced and stator windings are uniformly distributed and based on the well-known two-phase equivalent motor representation.

The mathematical model of the induction motor in the reference frame linked to the rotating field is obtained by considering the components of voltage (V_{ds}, V_{qs}) as control variables and (I_{ds}, I_{qs}, Φ_{dr}, Φ_{qr}, Ω) as state variables. This model is presented as follows [13, 30, 31, 32, 33, 34]:

$$\dot{x} = f(x) + g(x).u \tag{1}$$

Where :

$$x = (x_1, x_2, x_3, x_4, x_5)^T = (I_{ds}, I_{qs}, \Phi_{dr}, \Phi_{qr}, \Omega)^T$$

$$u = (u_1, u_2)^T = (V_{ds}, V_{qs})^T$$

With:

$$f(x)=\begin{pmatrix} f_1\\ f_2\\ f_3\\ f_4\\ f_5\end{pmatrix}=\begin{pmatrix} -\gamma I_{ds}+\omega_s I_{qs}+\frac{k}{T_r}\Phi_{dr}+pk\Phi_{qr}\Omega\\ -\gamma I_{qs}+\omega_s I_{ds}+\frac{k}{T_r}\Phi_{qr}+pk\Phi_{dr}\Omega\\ \frac{L_m}{T_r}I_{ds}-\frac{1}{T_r}\Phi_{dr}+(\omega_s-p\Omega)\Phi_{qr}\\ \frac{L_m}{T_r}I_{qs}-\frac{1}{T_r}\Phi_{qr}+(\omega_s-p\Omega)\Phi_{dr}\\ \frac{pL_m}{JL_r}\left(\Phi_{dr}I_{qs}-\Phi_{qr}I_{dr}\right)-\frac{C_r}{J}\end{pmatrix}$$

$$g(x)=\left(g_1(x)\quad g_2(x)\right)=\begin{pmatrix}\frac{1}{\sigma L_s} & 0\\ 0 & \frac{1}{\sigma L_s}\\ 0 & 0\\ 0 & 0\\ 0 & 0\end{pmatrix}$$

And :

$$T_r=\frac{L_r}{R_r};\sigma=1-\frac{L_m{}^2}{L_rL_s};k=\frac{L_m}{L_RL_s-L_m{}^2};$$

$$\gamma=\frac{1}{\sigma L_s}.\left(R_s-\frac{R_sL_m{}^2}{L_r{}^2}\right);\omega_{sl}=\omega_s-p.x_5$$

The induction motors have been used at a single speed, which was determined by the frequency of the main voltage and the number of poles. Controlling the speed of an induction motor is far more difficult than controlling the speed of a DC motor since there is no linear relationship between the motor current and the resulting torque as there is for a DC motor. Moreover, the dynamic behavior of an induction motor is complex due to the coupling effect between the stator and rotor phases. Therefore, to render the dynamics of the induction motor similar to the DC motor a vector control is required.

3. THE VECTOR CONTROL THEORY

The technique called vector control is used to vary the speed of an induction motor over a wide range. It was initially developed by Blaschke (1971-1973) [5]. The main objective of the vector control or field oriented control of induction motors is, as in DC machines, consists in the control of the torque and the flux independently; this can be done by using a d-q rotating reference frame synchronous [5]. To achieve field orientation, the flux (d axis) component of stator current I_{ds} is aligned in the direction of the rotor flux and the torque component of current I_{qs} is aligned in the direction perpendicular to it, at this condition [5, 13, 30, 31, 32, 33, 34].

$$\Phi_{dr}=\Phi_r \text{ and } \Phi_{qr}=0 \qquad (2)$$

The electromagnetic torque of field oriented induction motor is given by:

$$C_e=\frac{pL_m}{L_r}\Phi_r I_{qs} \qquad (3)$$

With vector control the dynamic equations of stator current components and rotor flux are given by (4):

$$\frac{d}{dt}\begin{pmatrix} I_{ds}\\ I_{qs}\\ \Phi_r\\ \Omega\end{pmatrix}=\begin{pmatrix} -\gamma I_{ds}+\omega_s I_{qs}+\frac{k}{T_r}\Phi_r+\frac{1}{\sigma L_s}V_{ds}\\ -\gamma I_{qs}-\omega_s I_{ds}-pk\Phi_r\Omega+\frac{1}{\sigma L_s}V_{qs}\\ \frac{L_m}{T_r}I_{ds}-\frac{1}{T_r}\Phi_r\\ \frac{pL_m}{JL_r}\Phi_r.I_{qs}-\frac{C_r}{J}\end{pmatrix} \qquad (4)$$

The vector control block is shown in Fig 1.

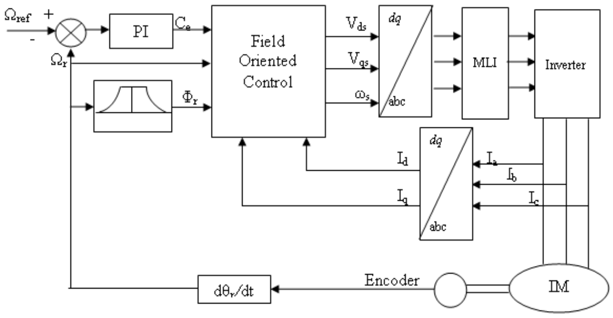


Fig. 1. Block diagram of the vector control.

4. TYPE-2 FUZZY LOGIC SYSTEMS

The interval type-2 FL is a special case of the type-2 FLS. It uses interval type-2 fuzzy sets to represent the inputs and/or outputs of the FL. The interval type-2 FL is depicted in Fig 2 and it consists of a Fuzzifier, Inference Engine, Rule Base, Type-reducer and Defuzzifier.

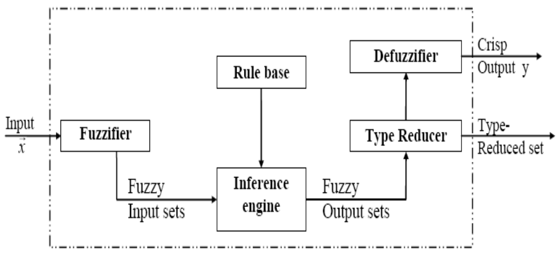


Fig. 2. Type-2 fuzzy logic system.

The interval type-2 FL works as follows: the crisp inputs from the input sensors are first fuzzified into input type-2 fuzzy sets; singleton fuzzification is usually used in interval type-2 FLC applications due to its simplicity and suitability for embedded processors and real-time applications. The input type-2 fuzzy sets then activate the inference engine and the rule base to produce output type-2 fuzzy sets. The type-2 FL rules will remain the same as in type-1 FL, but the antecedents and/or the consequents will be represented by interval type-2 fuzzy sets. The inference engine combines the fired rules and gives a mapping from input type-2 fuzzy sets to output type-2 fuzzy sets. The type-2 fuzzy outputs of the inference engine are then processed by the type-reducer [24]. The type reduction was proposed by Karnik and Mendel [33]. It is in extension of type-1 defuzzification method, and it is called type-reduction because this operation transforms type-2 output sets of the FLS to a type-1 set. Then, this set may be defuzzified to obtain a single crisp number. Many kinds of type-reduction [36, 37, 38] there exist. In this paper, we will use the center of sets type reduction.

In practice the computations in an IT2 FLS can be significantly simplified. Consider the rule base of an IT2 FLS consisting of N rules assuming the following form:

R^n: IF x_1 is $\widetilde{X}_1^n$ and…………..and x_I is $\widetilde{X}_I^n$, THEN y is Y^n n=1, 2…, N (5)

Where $\widetilde{X}_i^n$ (i=1…, I) are IT2FLS, and $Y^n = [\underline{y}^n, \overline{y}^n]$ is an interval.

Assume the input vector is $x' = (x'_1, x'_2, ..., x'_I)$. Typical computations in an IT2 FLS involve the following steps:

1) Compute the membership of x'_i on each X_i^n, $[\mu_{\underline{X}_i^n}(x'_i), \mu_{\overline{X}_i^n}(x'_i)]$, i=1,2,…, I, n=1,2,…,N

2) Compute the firing interval of the rule $F^n(x')$:

$$F^n(x') = [\mu_{\underline{X}_1^n}(x'_1) \times .....\times \mu_{\underline{X}_I^n}(x'_I), \mu_{\overline{X}_1^n}(x'_1) \times ...\times \mu_{\overline{X}_I^n}(x'_I)] \equiv [\underline{f}^n, \overline{f}^n]$$

n=1,…, N (6)

Note that the minimum, instead of the product, can be used in (6).

3) Perform type-reduction to combine $F^n(x')$ and the corresponding rule consequents. There are many such methods. The most commonly used one is the centre-of-sets type-reducer, this method is proposed by Karnik and Mendel [25, 39].

$$Y_{\cos}(x') = \bigcup_{\substack{f^n \in F^n(x') \\ y^n \in Y^n}} \frac{\sum_{n=1}^{N} f^n y^n}{f^n} = [y_l, y_r] \quad (7)$$

4) Compute the defuzzified output as:

$$y = \frac{y_l + y_r}{2} \quad (8)$$

5. APPLICATION OF THE INTERVAL TYPE-2 FUZZY LOGIC TO THE CONTROL OF THE INDUCTION MOTOR

The vector control requires a precise knowledge of the motor parameters, the variation of these parameters degrades its performance. The Interval type-2 Fuzzy logic is applied to the vector control by replacing the block of FOC by a fuzzy vector control block taking account of the parametric variation.

We chose for the model:

- A limited number of fuzzy sets, three or five for each variable.
- The membership functions of the fuzzy sets are Trapezoidal and Triangular shape for the input variables.

The expression of the vector control is written as follows (9):

$$y = f(x) \quad (9)$$

Where:

$$y = (V_{ds}, V_{qs}, \omega_s)^t; x = \left(C_e, \frac{dC_e}{dt}, \Phi_r, \frac{d\Phi_r}{dt}, \Omega\right)^t$$

Considering that the flux of reference Φ_r is constant, this means that:

$$\frac{d\Phi_r}{dt} = 0 \quad (10)$$

The new input variable is given as follows:

$$x = \left(C_e, \frac{dC_e}{dt}, \Phi_r, \Omega\right)^t \quad (11)$$

The system of equations which characterize the model is given by (12):

$$f_1(x) = V_{ds} = \frac{R_s}{L_m}\Phi_r - \frac{R_r\left(L_sL_r - L_m^2\right)}{L_m p^2}\frac{C_e^2}{\Phi_r^3} - \frac{\left(L_sL_r - L_m\right)}{L_m}\Omega\frac{C_e}{\Phi_r}$$

$$f_2(x) = V_{qs} = \frac{pL_s}{L_m}\Omega\Phi_r - \frac{\left(L_sL_r + L_sR_r\right)}{L_m p}\frac{C_e}{\Phi_r} - \frac{\left(L_sL_r - L_m^2\right)}{L_m p}\frac{1}{\Phi_r}\frac{dC_e}{dt} \quad (12)$$

$$f3(x) = \omega_s = \frac{R_r}{p}\frac{C_e}{\Phi_r^2} + p\Omega$$

However, it remains to conceive the fuzzy representation of the system; this representation gathers all uncertainties of the system defined by:

$$\tilde{y} = \begin{pmatrix}\tilde{V}_{ds}\\ \tilde{V}_{qs}\\ \tilde{\omega}_s\end{pmatrix} = \tilde{f}(\tilde{x}) = \begin{pmatrix}\tilde{f}_1\left(\tilde{C}_e,\tilde{\Phi}_r,\tilde{\Omega}\right)\\ \tilde{f}_2\left(\tilde{C}_e,\dfrac{d\tilde{C}_e}{dt},\tilde{\Phi}_r,\tilde{\Omega}\right)\\ \tilde{f}_3\left(\tilde{C}_e,\tilde{\Phi}_r,\tilde{\Omega}\right)\end{pmatrix} \quad (13)$$

With $\tilde{C}_e, \frac{d\tilde{C}_e}{dt}, \tilde{\Phi}_r, \tilde{\Omega}$ and $\tilde{V}_{ds}, \tilde{V}_{qs}, \tilde{\omega}_s$ are fuzzy variables corresponding to the input variables $C_e, \frac{dC_e}{dt}, \Phi_r, \Omega$ and to the control variables V_{ds}, V_{qs}, ω_s respectively.

The rules are then presented as follows:

$\Re^{(k1,\ldots,k4)}_{V_{ds}}$: **IF** (C_e, Φ_r, Ω) is $\left(\tilde{F}^{k1}_{Ce}, \tilde{F}^{k3}_{\Phi r}, \tilde{F}^{k4}_{\Omega}\right)$ **THEN** V_{ds} is $\tilde{Y}^{(k1,k3,k4)}_{V_{ds}}$

$\Re^{(k1,\ldots,k4)}_{V_{qs}}$: **IF** $\left(C_e, \frac{dC_e}{dt}, \Phi_r, \Omega\right)$ is $\left(\tilde{F}^{k1}_{Ce}, \tilde{F}^{k2}_{dCe}\tilde{F}^{k3}_{\Phi r}, \tilde{F}^{k4}_{\Omega}\right)$ **THEN** V_{qs} is $\tilde{Y}^{(k1,k2,k3,k4)}_{V_{qs}}$

$\Re^{(k1,\ldots,k4)}_{\omega_s}$: **IF** (C_e, Φ_r, Ω) is $\left(\tilde{F}^{k1}_{Ce}, \tilde{F}^{k3}_{\Phi r}, \tilde{F}^{k4}_{\Omega}\right)$ **THEN** ω_s is $\tilde{Y}^{(k1,k3,k4)}_{\omega_s}$

Where $\tilde{F}^{k1}_{Ce}, \tilde{F}^{k2}_{dCe}\tilde{F}^{k3}_{\Phi r}, \tilde{F}^{k4}_{\Omega}, \tilde{Y}^{(k1,k3,k4)}_{V_{ds}}, \tilde{Y}^{(k1,k2,k3,k4)}_{V_{qs}}$ and $\tilde{Y}^{(k1,k3,k4)}_{\omega_s}$ are IT2 FSs.

For the output, we transform a type-2 fuzzy set into type-1 fuzzy set using the method of centers sets:

$$Y_{\cos}(x') = \bigcup_{\substack{f^n \in F^n(x')\\ y^n \in Y^n}} \frac{\sum_{n=1}^{N} f^n{}_{(Ce,dCe,\Phi r,\Omega)}\, y^n{}_{(Vds,Vqs,\omega s)}}{f^n{}_{(Ce,dCe,\Phi r,\Omega)}} = [y_{l(Vds,Vqs,\omega s)}, y_{r(Vds,Vqs,\omega s)}$$

The defuzzified output of y will be the average of y_l and y_r:

$$y_{(Vds,Vqs,\omega s)} = \frac{y_{l(Vds,Vqs,\omega s)} + y_{r(Vds,Vqs,\omega s)}}{2} \quad (16)$$

The block diagram corresponding to the Interval type-2 fuzzy model is shown in Fig 3.

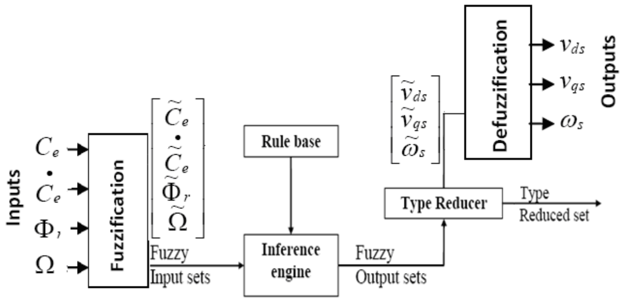


Fig. 3. Block diagram of the Interval type-2 fuzzy control replaces the vector control.

This new model (Fig. 4) has an Interval type-2 fuzzy control algorithm which updates the values of the stator voltage and the synchronous pulse. This new block has four inputs and three outputs. The inputs are the electromagnetic torque, the derivative of electromagnetic torque, the rotor flux and rotor speed, with each of these inputs corresponding to a fuzzy variable (Fig. 5). The output is the fuzzy control decision.

Theoretically, it is interesting to note that when the number of fuzzy sets of inputs increases, the approximation obtained is better. However, we couldn't exceed a certain number of fuzzy sets, we risk losing the utilities of fuzzy logic, among other things such as the increase in computing time.

Consequently, it would be judicious to reduce the complexity of the Interval type-2 fuzzy model. The easiest method consists in subdividing the model in several blocks. In our case, we chose a three under-block as shown in Fig 6.

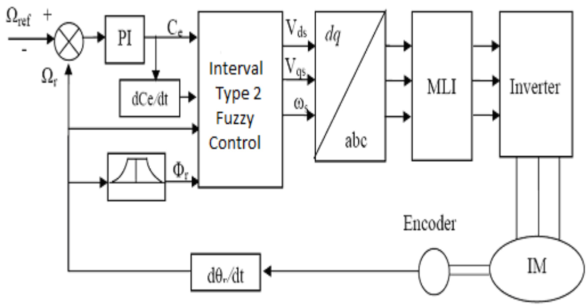
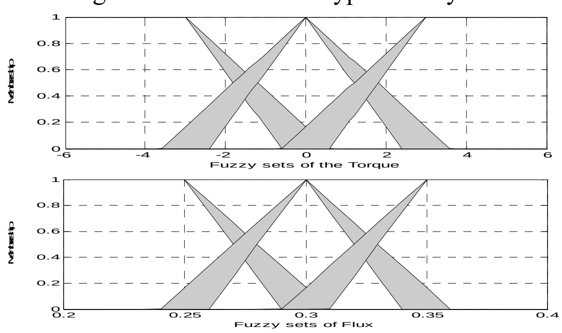


Fig. 4. The new vector type-2 fuzzy control.



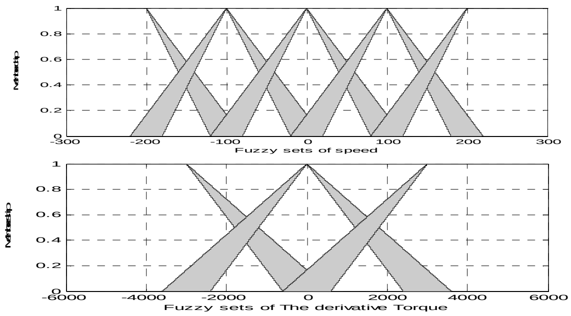


Fig. 5. The membership of the inputs.

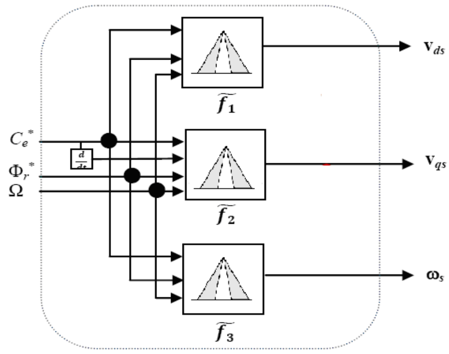
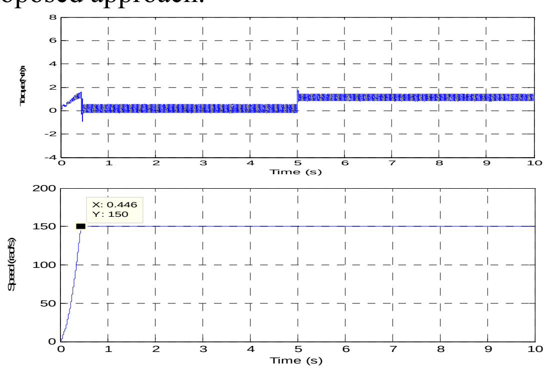


Fig. 6. Decomposition of Interval type-2 fuzzy model into sub-fuzzy systems.

5. SIMULATION RESULTS

In order to verify the effectiveness of the proposed approach, some simulation studies were carried out using MATLAB/SIMULINK. The induction motor used in the simulation is a 2-pole machine with a 1.5 kW rated power and 1423 rpm rated rotational speed. The test concerns a no-load starting of the motor with a reference speed Ω_{ref}= 150 rad/sec and reference rotor flux ϕ_r=0.3 Wb, then a load torque of 1 Nm is applied at 5 sec.

In the Fig 7, the application of the load torque causes a step change in the electromagnetic torque response without any effects on the flux responses, which are maintained constant, due to the decoupled control introduced by the proposed approach. So, these characteristics are similar to those obtained with a vector control technique, which is the aim of the proposed approach.



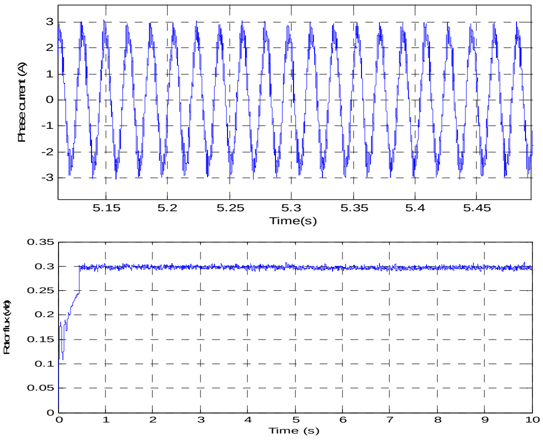


Fig. 7. The performance of the interval type-2 fuzzy vector control.

In the Fig.8, the performance of the fuzzy vector control is shown at low speed. These results show that using the interval type-2 fuzzy control at low speed give the better performance with maintaining decoupling.

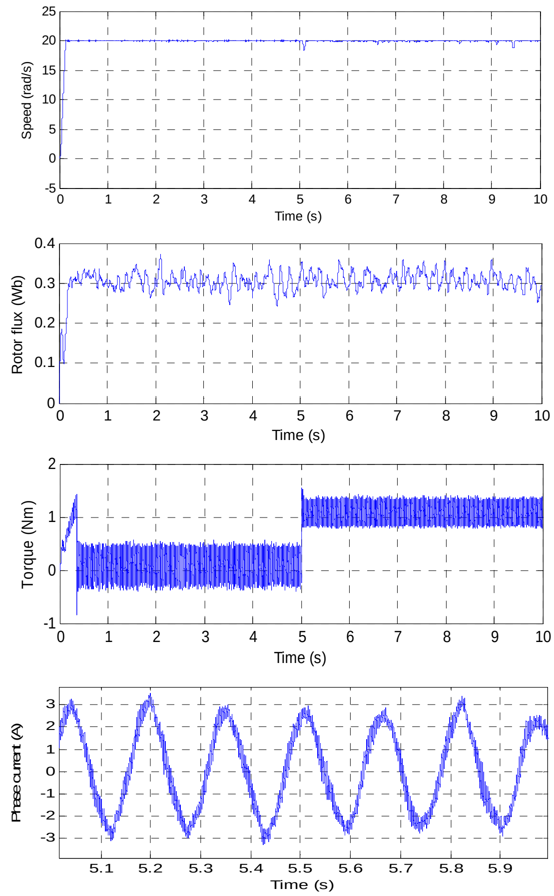
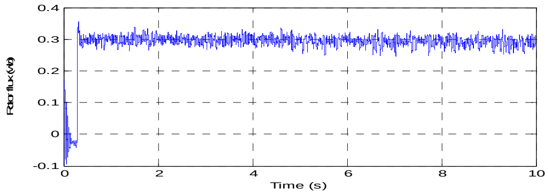
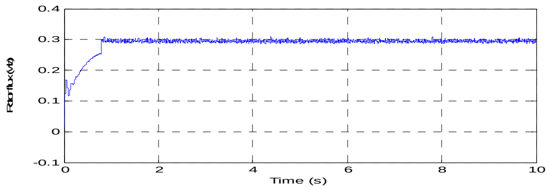


Fig. 8. The performance of the interval type-2 fuzzy vector control at low speed.

In this simulation, VC only incorporates proportional integral current regulators. The comparisons between the two control techniques show that the flux ripple is more significant in the case of vector control (Fig. 8).



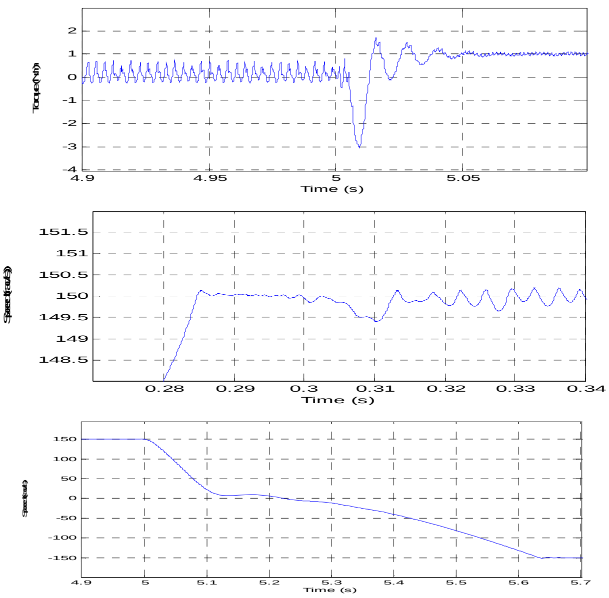
a) Classical Vector control



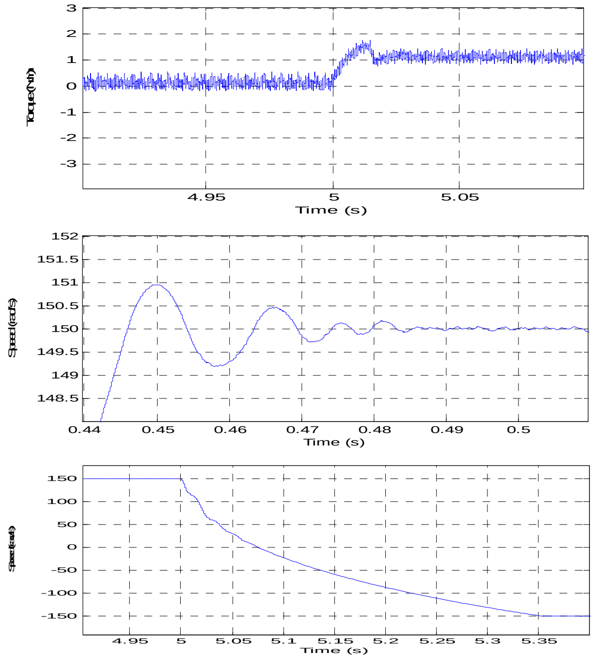
b) Interval type-2 fuzzy vector control

Fig. 9. The flux response of the two control techniques.

The transient performance of the two schemes has been compared through the motor torque response to a variation step of the torque reference starting from 0 Nm to 1 Nm and with the same parameters of the PI regulator. These results show that using the type-2 fuzzy control scheme can be achieved a better torque response in terms of settling time without major overshoot in comparison with classical vector control. In addition, the type-2 fuzzy control presents less ripple of the speed compared to the vector control. It can be seen also the better performance in the fuzzy control when the changing of the rotational direction of the induction motor within 0.35 seconds (Fig .9).



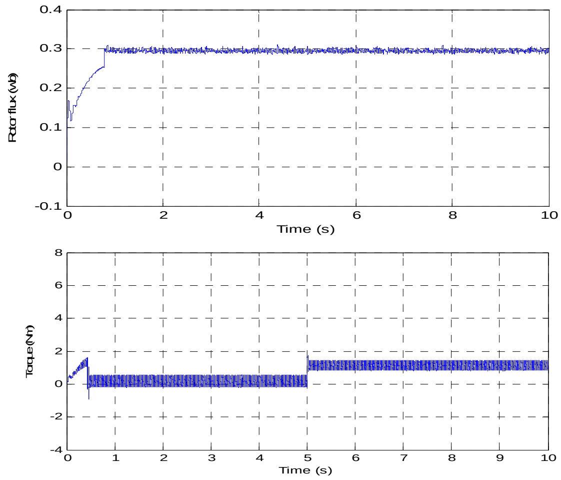
a) Classical Vector control



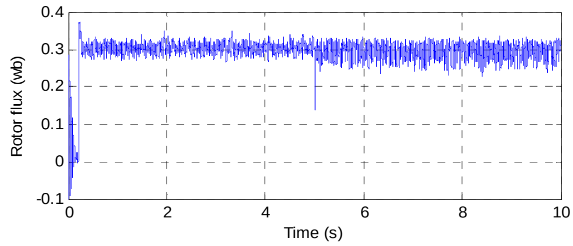
b) Interval type-2 fuzzy vector control

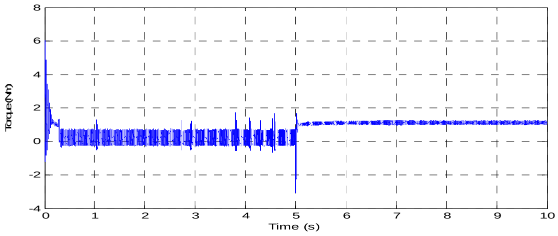
Fig. 10. The torque response of the two control techniques.

When the rotor resistance increases, the time constant decreases, the rotor flux is affected and it decreases. As a result, we lose the decoupling. The Fig 10 shows that decoupling is maintained for the fuzzy control in spite of an increase in resistance to 50% of its real value.



a) Performance of the fuzzy vector control with +50% of Rr.





b) Performance of the vector control with +50% of Rr.

Fig. 11. Performance of the two control techniques with variation parametric.

The robustness of the fuzzy vector control is confirmed with the variation of the rotor resistance and the moment of inertia in terms of rise time and overshoot of the speed.

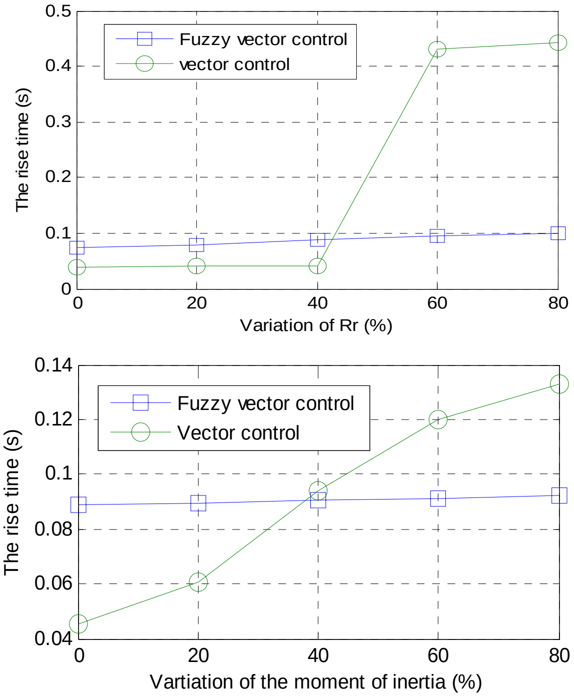
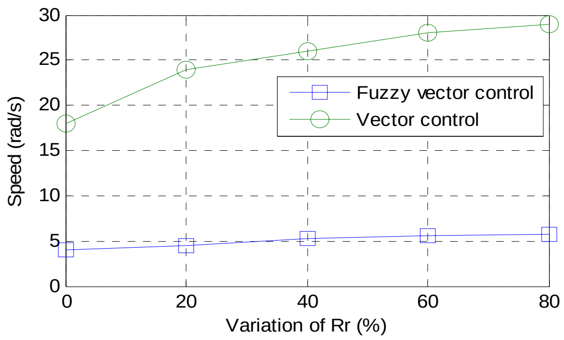


Fig. 12. The rise time.



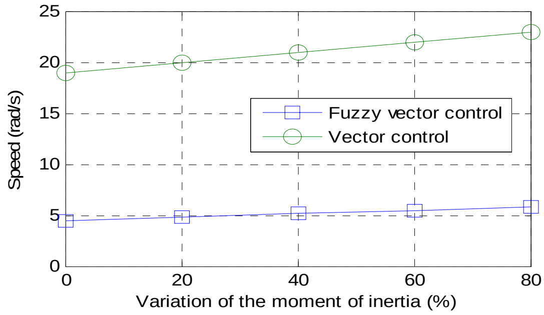


Fig. 13. The Overshoot of the speed.

6. CONCLUSION

The validity of the proposed control technique has been established both in simulation at different operating conditions. This control technique has revealed very interesting characteristics. The novelty in this control, compared to previous works in the literature, is to replace the FOC block by the fuzzy logic block to control the induction motor. This control maintains the decoupling and provides a high dynamic and statistic performance. Furthermore, compared with the conventional vector control, the fuzzy vector control is simple to implement as it uses a reduced model, reduced time of simulation and its insensitivity to parametric variation. Another advantage of this control is the absence of d-q current regulators. Therefore, leading the induction motor with fuzzy control presents a low cost system for many applications. Currently, we are working on the real time implementation of this approach on benchmark designed in our laboratory.

APPENDIX

1) Nomenclature:

Rs, Rr: stator and rotor resistances, respectively,
Ls, Lr: stator and rotor inductances, respectively,
L_m: mutual inductance,
J: moment of inertia,
P: the number of pole pairs,
Ω: rotor speed,
Φ_{dr}, Φ_{qr}: rotor flux d-q components,
I_{ds}, I_{qs}: stator current components,
V_{ds}, V_{qs}: stator voltage components (control signals),
Φ_r: reference rotor flux,
Ω_{ref}: reference rotor speed,
C_r: the load torque,
C_e: the electromagnetic torque,
ω_s: stator pulsation.

2) The motor data are as follows:

Electric power: P =1.5KW,
Stator voltage: V = 380 / 220V,
Number of Poles: p = 2,
Rated speed: Ω =150 rad/sec,
Frequency: f = 50Hz,
Stator resistance: Rs = 4.70Ω,

Rotor resistance: Rr = 4.32Ω,
Stator inductance: Ls = 0.276H,
Rotor inductance: Lr = 0.276H,
Mutual inductance: Lm = 0.262H,
Moment of inertia: J = 0.0023kg.m^2,
Viscous friction coefficient f=0.00088 Nms.

REFERENCES

[1] Ramón Blasco Giménez, *High performance sensorless vector control of induction motor drives*, Thesis of the University of Nottingham, December, 1995.

[2] Alma Y. Alanis, *Real-time Discrete Backstepping Neural Control for Induction Motors*, IEEE Trans on control syst technology, vol. 19, pp. 359 – 366, 2011.

[3] Tian-Jun Fu, Wen-Fang XieA, *novel sliding-mode control of induction motor using space vector modulation technique*, ISA Trans, vol. 44, pp. 481–490, 2005.

[4] Ramzi Trabelsi and all, *Backstepping control for an induction motor using an adaptive sliding rotor-flux observer*, Electric Pow Syst Res, vol. 93, pp. 1-15, 2012.

[5] F. Blaschke, *The principle of field orientation applied to the new transvector closed-loop control system for rotating field machines*, Siemens-Rev, vol. 39, pp. 217-220, 1972.

[6] Alma Y Alanis, *Real-time Discrete Backstepping Neural Control for Induction Motors*. IEEE Transactions on control systems technology, vol. 19, pp. 359 – 366, 2011.

[7] Jinpeng Yu, Bing Chen, Haisheng Yu. *Position tracking control of induction motors via adaptive fuzzy backstepping,* Energy Conversion and Management, vol. 51, pp. 2345–2352, 2010.

[8] Ezziani N, Essounbouli N, Hamzaoui A. *Backstepping fuzzy adaptive controller of induction machine*, 16th Mediterranean Conference on Control and Automation, pp. 1622 – 1627, 2008.

[9] B. K. Bose, *Sliding mode control of induction motor*, in Proc. IEEE-IAS Annu. Meeting, pp.1985-1998, 2007.

[10] W. J. Wang and J. Y. Chen, *A new sliding mode position controller with adaptive load torque estimator for an induction motor*, IEEE Trans. Energy Convers, Vol. 14, pp. 413-418, 1999.

[11] Mao-Fu Lai, Chen Chang, Wen-Yuh Chiou, *Design of fuzzy logic controller for an induction motor speed drive*, SICE '97. Proceedings of the 36th SICE Annual Conference, pp 1071 – 1076, 1997.

[12] Sang Hoon Kim, Lark Kyo Kim, *Design of a neuro-fuzzy controller for speed control applied to AC servo motor*, IEEE International Symposium on Industrial Electronics, pp 435 – 440, 2001.

[13] S. Amamra, L. Barazane, M.S. Boucherit, *A New Approach of the Vector Control of the Induction Motor Using an Inverse Fuzzy Model*, International Review of Electrical Engineering, 2008.

[14] K. Mohanasundaram and all, *A Fuzzy Logic Approach for Speed Controller Design of A.C. Voltage Controller Fed Induction Motor Drive*, Fifth International Conference on MEMS, NANO, and Smart Systems, pp 133 – 136, 2009.

[15] M. Manceur, N. Essounbouli and A. Hamzaoui, *Second Order Sliding Fuzzy Interval Type-2 Control For Uncertain System With Real Application*, IEEE Trans on Fuzzy Syst, vol.20, pp. 262-275, 2012.

[16] L.X Wang, *Fuzzy systems are universal approximators*, IEEE Inter Conf on Fuzzy Syst, San Diego, USA, pp. 1163-1169, 1992.

[17] Hakju Lee, Jaedo Lee, Sejin Seong, *Approach to Fuzzy Control of an Indirect Field-Oriented Induction Motor Drives*, IEEE International Symposium on Industrial Electronics, pp 1119-1123, 2001.

[18] Divya Asija, *Speed Control of Induction Motor Using Fuzzy-PI Controller*, 2nd International Conference on Mechanical and Electronics Engineering, pp 460-463, 2010.

[19] Biranchi Narayan Kar and all, *Indirect Vector Control of Induction Motor Using Fuzzy Logic Controller*, 10th International Conference on Environment and Electrical Engineering (EEEIC), pp 1-4, 2011.

[20] Yung-Chang Luo, Wei-Xian Chen, *Sensorless stator field orientation controlled induction motor drive with a fuzzy speed controller*, Computers and Mathematics with Applications, pp 1206-1216, 2012.

[21] K Chafaa, L Saidi, M Ghanai and K Benmahammed, *Indirect adaptive interval Type-2 fuzzy control for nonlinear systems*, International Journal of Modelling, Identification and Control, vol. 2, pp. 106–119, 2007.

[22] E. Nechadi, N. Essounbouli and A. Hamzaoui, *Type-2 fuzzy based adaptive synergetic power system control*, Electric Pow Syst Res, vol. 88, pp. 9-15, 2012.

[23] H. Hagras, *A hierarchical type-2 fuzzy logic control architecture for autonomous mobile robots*, IEEE Trans on Fuzzy Syst, vol. 12, pp. 524–539, 2004.

[24] H. Hagras, *Type-2 FLCs: A new generation of fuzzy controllers*, IEEE Computational Intelligence Magazine, vol. 2, pp. 30–43, 2007.

[25] J. Mendel, *Uncertain rule-based fuzzy logic systems: introduction and new directions*, Prentice-Hall, Upper Saddle River, NJ, 2001.

[26] D. Wu and W. W. Tan, *Genetic learning and performance evaluation of type-2 fuzzy logic controllers*, Engineering Applications of Artificial Intelligence, vol. 19, pp. 829–841, 2006.

[27] L. Zadeh, *The concept of a linguistic variable and its application to approximate reasoning,* Information sciences, vol. 8, pp.199-249, 1975.

[28] N. Karnik and J. Mendel, *Introduction to type-2 fuzzy logic systems*, In Fuzzy Systems Proceedings IEEE World Congress on Computational Intelligence, vol. 2, pp. 915-920, 1998.

[29] J, Mendel, *An introduction to type-2 fuzzy logic systems,* Univ Southern California, Los Angeles, CA.

[30] W. Leonhard, “Control of Electric Drives”, *Springer-Verlag*, Germany, 1995.

[31] L. Barazane, C. Larbes and M.S. Boucherit, *Robust hybrid control based on feedback linearization and field-oriented controls of induction motor*, Archives of Electrical Engineering, vol.2, pp. 115-135, 2003.

[32] J. Bocker, S. Mathapati, *State of The Art of Induction motor Control*, IEEE Trans on Industrial Electronics, vol. 5, pp. 1459-1464, 2007.

[33] S. Peresada, A. Tilli, and A. Tonielli, *Theoretical and Experimental Comparison of Indirect Field-Oriented Controllers for Induction Motors*, IEEE Trans on Pow Electronics, vol.18, pp.151-163, 2003.

[34] A.K. Rathore, *Improved Performance of Fuzzy Logic Based Direct Field Oriented Controlled Induction Motor*, 9th IEEE International Power Electronics Congress, pp. 152-157, 2004.

[35] N.N. Karnik, J.M. Mendel and Q. Liang, *Type-2 fuzzy logic systems*, IEEE Trans on Fuzzy Syst, vol.7, pp. 643–658, 1999.

[36] J, Mendel, *Computing derivatives in interval type-2 fuzzy logic systems*, IEEE Trans on Fuzzy Syst, vol.12, pp. 84–98, 2004

[37] D. Wu and J. Mendel, *Enhanced Karnik-Mendel Algorithms*, IEEE Trans on Fuzzy Syst, vol.17, pp. 923–934, 2009.

[38] O. Mendoza, P. Melín, and O. Castillo, *Interval type-2 fuzzy logic and modular neural networks for face recognition applications,* Applied Soft Computing, vol. 9, pp. 1377-1387, 2009.

[39] N. Karnik and J. Mendel, *Applications of type-2 fuzzy logic systems: Handling the uncertainty associated with surveys*, In Fuzzy Systems Conference Proceedings, pp 1546-1551, 1999.