Sensorless Speed Control of Induction Motor Using DTFC based Fuzzy Logic

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Abstract**—** This paper presents the sensorless speed control performance of an improved direct torque and flux control (DTFC) for induction motor. The proposed DTFC is based on fuzzy logic technique to replace switching table and hysteresis regulator, in order to reduce torque and flux ripples in comparison with the conventional DTFC. We estimated the rotor speed by using the Model Reference Adaptive Systems (MRAS). Several strategies of speed control are presented and tested: Proportional Integral regulator (PI) anti-windup, PI with and without saturation and PI fuzzy logic. The validity of proposed technique is verified by simulation results using Matlab/Simulink.

Keywords**—**Induction Motor, sensorless DTFC, Fuzzy Logic technique, Speed Control, Anti-windup, PI Fuzzy Logic, MRAS.

I. INTRODUCTION

Induction motors are more and more used in industry because they are more rugged and reliable than DC machines. However, its dynamic behavior is considerably more complex than that of a DC machine due to the highly non-linear and time varying mathematical equations of the induction machine [1-2]. Therefore, Induction motors are often used in closed-loop for adjustable speed applications [3] while DC machines [4] or stepping motors [5] are preferred for high precision positioning tasks. Nevertheless, with the recent advances made in both power electronics, data processing and control strategy, the speed control of induction motors can be considered.

High performance electric drives require decoupled torque and flux control. This control is commonly provided through Field Oriented Control (FOC), which is based on decoupling of the torque-producing current component and the flux-producing component. FOC drive scheme requires current controllers and coordinate transformations. Current-regulated pulse-width-modulation inverter and inner current loops degrade the dynamic performance in the operating regimes wherein the voltage margin is insufficient for the current control, particularly in the field weakening region [6].

The problem of decoupling the stator current in a dynamic fashion is avoided by DTFC. Direct Torque and Flux Control (DTFC) is nowadays widely used for induction motor drives, her provides a very quick and precise torque response without the complex field orientation block and the inner current regulation loop [7]. The disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up [8]. For that reason the application of Fuzzy logic attracts the attention of many scientists from all over the word. The fuzzy logic control strategy [7-9] has been chosen for it simplicity and its robustness to external and plant parameters disturbances. Indeed, the fuzzy logic theory offers the advantage of requiring only a simple mathematical model to formulate the algorithm. These features are appreciated for non-linear processes for which there is no reliable model and for fast processes such as the induction motor.

On the other hand, ongoing research has concentrated on the elimination of the speed sensor at the machine shaft without deteriorating the dynamic performance of the drive control system [15]. The advantages of speed sensorless induction motor drives are reduced hardware complexity and lower cost, reduced size of the drive machine, elimination of the sensor cable, better noise immunity, increased reliability and less maintenance requirements.

In this paper we present the performance of the sensorless speed control of induction motor using a several strategies of speed control. The Fuzzy Logic technique then replaces the switching table and hysteresis regulator of the conventional DTFC while the rotation speed is estimated by the MRAS method. This paper organized as follows: The induction model is presented in the second section, the DTFC based Fuzzy Logic is developed in the third section, section fourth present a speed MRAS estimator, the speed control methods are performed in the five section, and section six is devoted to illustrating by simulation the performances of this control strategy, a conclusion and reference list end the paper.

II. INDUCTION MOTOR MODEL

The state equation of induction motor written in stator reference frame, (α, β) coordinates, can be expressed as follows:

$$\begin{cases} \dot{X} = A(\omega).X + B.U \\ Y = C.X \end{cases} \tag{1}$$

Where A, B and C are the evolution, the control and the observation matrices respectively.

$$X = [i_{s\alpha} \quad i_{s\beta} \quad \Phi_{s\alpha} \quad \Phi_{s\beta}]\ ; U = \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix}; Y = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}$$

$$A=\begin{bmatrix} -(\frac{1}{\sigma T_s}+\frac{1-\sigma}{\sigma T_r}) & 0 & \frac{1-\sigma}{\sigma M T_r} & \frac{1-\sigma}{\sigma M}\omega \\ 0 & -(\frac{1}{\sigma T_s}+\frac{1-\sigma}{\sigma T_r}) & -\frac{1-\sigma}{\sigma M}\omega & \frac{1-\sigma}{\sigma M T_r}\omega \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & -\omega \\ 0 & \frac{M}{T_r} & \omega & -\frac{1}{T_r} \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad C=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

With, ω Rotor speed and the machine's parameters: R_s, R_r are respectively the stator and the rotor resistance, M, L_s, L_r are respectively the mutual, the stator and the rotor cyclic inductances; p denotes the number of pole pairs, with:

$$T_r=\frac{L_r}{R_r},\ T_s=\frac{L_s}{R_s},\ \sigma=1-\frac{M^2}{L_s L_r}$$

The mechanical equation is the following:

$$J.\frac{d}{dt}\Omega=C_e-C_r-f.\Omega \qquad (2)$$

In which J is the inertia coefficient and C_r is the load torque. Using the Laplace transform, the equation (3) shows that the relation between the stator flux and the rotor flux represents a low pass with time constant σT_r.

$$\overline{\Phi}_r=\frac{M}{L_s}\frac{\overline{\Phi}_s}{1+\sigma T_r s} \qquad (3)$$

The electromagnetic torque can be expressed as

$$C_e=\frac{3}{2}\frac{p}{2}(\Phi_{s\alpha}.i_{s\beta}-\Phi_{s\beta}.i_{s\alpha}) \qquad (4)$$

III. DIRECT TORQUE AND FLUX CONTROL STRATEGY

A. Principle of the DTFC

The block diagram of the proposed sensorless control scheme is shown in figure 1. The DTFC method was introduced in 1985 by Takahashi [16]. This strategy of control is relatively new and competitive compare to the rotor flux oriented method.

This type of control is based on the directly determination of the sequence of control applied to the switches of a tension inverter. This choice is generally based on the use of hysteresis regulators, whose function is to control the state of the system, and to modify the amplitude of the stator flux and the electromagnetic torque.

The stator flux, as given in equation (5), can be approximated as equation (6) over a short time period if the stator resistance is ignored.

$$\overline{\Phi}_s=\overline{\Phi}_{so}+\int_0^t(\overline{V}_s-R_s\overline{I}_s)dt \qquad (5)$$

$$\overline{\Phi}_s\approx\overline{\Phi}_{so}+\int_0^t\overline{V}_s dt \qquad (6)$$

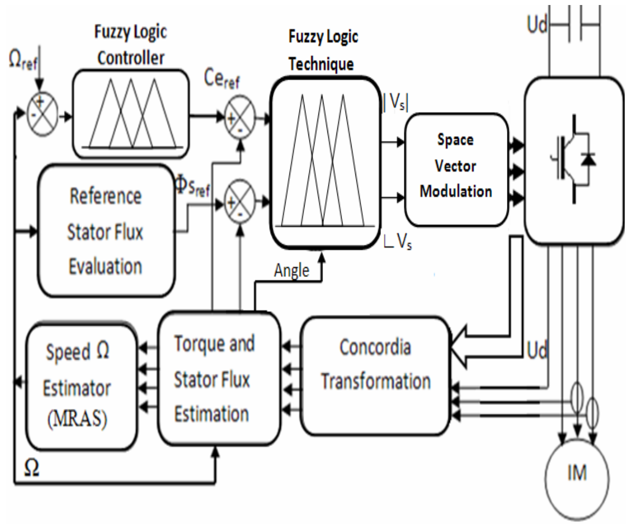

Fig. 1. Block diagram of sensorless control proposed

During one period of sampling Te, vector tension applied to the machine remains constant, and thus one can write

$$\overline{\Phi}_s(k+1)\approx\overline{\Phi}_s(k)+\overline{V}_s.T_e \qquad (7)$$

$$\text{Or}\quad \Delta\overline{\Phi}_s\approx\overline{V}_s.T_e \qquad (8)$$

Therefore to increase the stator flux, we can apply a vector of tension that is co-linear in its direction and vice-versa.

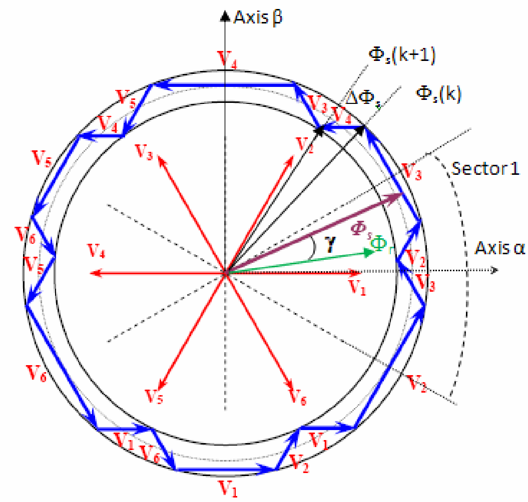

Fig. 2. Definition of stator flux increment and spatial positions of the voltage vectors keeping the flux inside the strip of hysteresis.

If the error of flux is projected on the direction of stator flux and on a perpendicular direction (Fig.3), one puts in evidence the components acting on the torque and on the flux. In the Figure 3, the component $\Delta\Phi_{sc}$ gives the electromagnetic

Torque of the Induction motor while the component $\Delta\Phi_{sf}$ modifies the magnitude of stator flux.

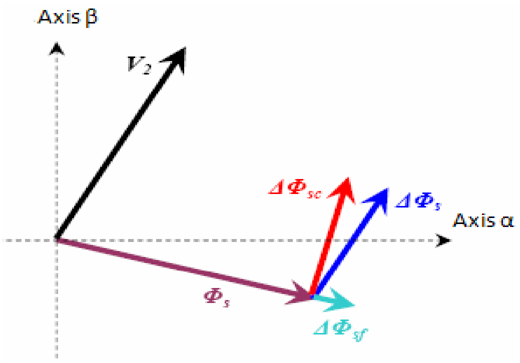

Fig. 3. Components of the error of flux at the time of the application of the vector V_2 voltage

The torque is produced by the induction motor can be expressed as equation:

$$Ce = \frac{3}{2} p \frac{M}{\sigma L_s L_r} \Phi_s \Phi_r \sin \gamma \qquad (9)$$

The torque depends upon the amplitude of the two vectors stator flux $\overline{\Phi}_s$ and rotor flux $\overline{\Phi}_r$, and their relative position γ. If one succeeds in perfectly controlling the flux $\overline{\Phi}_s$ (starting with Vs) in module and in position, one can subsequently control the amplitude and the relative position of Φ_r and therefore ultimately, the torque.

When flux is in sector S_i, the vectors V_{i+1} or V_{i-1} are selected to increase the amplitude of flux, and V_{i+2} or V_{i-2} to decrease it. What shows that the choice of the vector tension depends on the sign of the error of flux, independently of its amplitude. This explains why the exit of the corrector of flux can be a Boolean variable. One adds a bond of hysteresis around zero to avoid useless commutations when the error of flux is small. Indeed, with this type of corrector in spite of his simplicity, one can easily control and maintain the end of the vector flux, in a circular ring. The switching table proposed by Takahashi [16], as given by Table 1.

$\Delta\phi_s$	ΔC_e	S_1	S_2	S_3	S_4	S_5	S_6
1	1	110	010	011	001	101	100
	0	000	000	000	000	000	000
	-1	101	100	110	010	011	001
0	1	010	011	001	101	100	110
	0	000	000	000	000	000	000
	-1	001	101	100	110	010	011

Table1. Switching table

B. DTFC based Fuzzy Logic

To obtain improved performance of the DTFC drive during start-up or during changes in the reference flux and torque, the authors propose a DTFC based fuzzy logic strategy using space vector modulation also for more advantages [13]: Fast torque response, reduce current distortion and torque ripple and constant switching frequency.

The block diagram of the proposed Fuzzy controller is shown in figure 4. The fuzzy controller is designed to have three fuzzy state variables and two control variables for achieving direct torque and flux control of the induction machine,

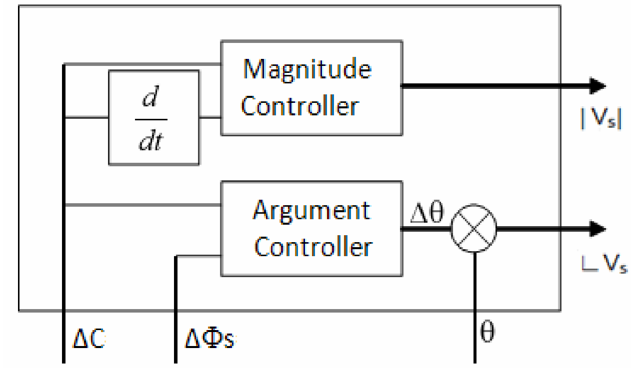

Fig.4. Fuzzy Controller

There are three variable input fuzzy logic controllers, the electromagnetic torque error (**ΔC=Ce$_{ref}$ - Ce**), the stator flux error (**ΔΦs=Φs$_{ref}$ - Φs**) and angle of stator flux (**θ**). The output it is the magnitude and argument of voltage vector reference for space vector modulation.

For this purpose, a Mamdani type fuzzy logic system will be used and a rule base has to be formulated, where the different voltage states are selected by using the torque and flux errors and also the position of the stator flux linkage space vector.

The output of the argument fuzzy controller is not the control variable itself but its increment (**Δθ**)

Figure 5 represents the membership functions of the different variables. Universe of discourse is devised in two functions: Dec: Decrease and Inc: Increase

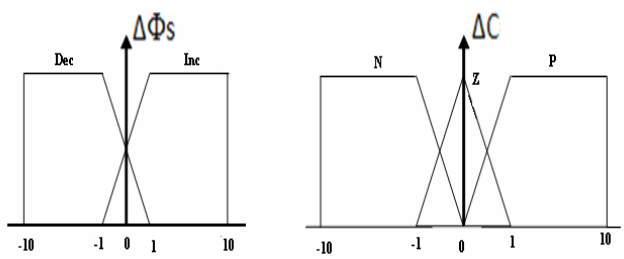

Fig.5. Membership functions for ΔΦs and ΔC

The fuzzy argument controller rules are given in the table 2:

- If the torque must be increased and the flux must be increased, we apply a voltage vector argument equal to the flux argument increased of Π/3.
- If the torque must be increased and the flux must be decreased, we apply a voltage vector argument equal to the flux argument increased of 2Π/3.
- If the torque must be decreased and the flux must be increased, we apply a voltage vector argument equal to the flux argument decreased of Π/3.

- If the torque must be decreased and the flux must be decreased, we apply a voltage vector argument equal to the flux argument decreased of 2Π/3.

<table>
<tr><td colspan="2" rowspan="2">Δθ</td><td colspan="2">ΔΦs</td></tr>
<tr><td>Dec</td><td>Inc</td></tr>
<tr><td rowspan="2">ΔC</td><td>Dec</td><td>μ(-2π/3)</td><td>μ(-π/3)</td></tr>
<tr><td>Inc</td><td>μ(2π/3)</td><td>μ(π/3)</td></tr>
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Table 2. Argument Controller fuzzy rules

Figure 6 shows the membership functions for output variable of argument controller,

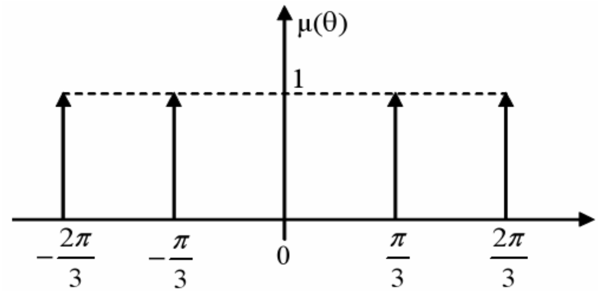

Fig.6. membership functions for output Argument controller

In the conventional DTC, the voltage vectors have constant amplitude. In this approach, this amplitude is modified with torque error and its derivative.

The linguistic rules are in the form of IF-THEN rules and take form:

IF (ΔC Dec and $\frac{d(\Delta C)}{dt} < 0$) THEN magnitude voltage vector is small.

In Table 3, the following fuzzy sets are used: N negative, M medium, Z zero, P positive, S small and L large.

<table>
<tr><td colspan="2" rowspan="2">V</td><td colspan="3">$\frac{d}{dt}(\Delta C)$</td></tr>
<tr><td>N</td><td>Z</td><td>P</td></tr>
<tr><td rowspan="2">ΔC</td><td>Dec</td><td>S</td><td>S</td><td>M</td></tr>
<tr><td>Inc</td><td>M</td><td>L</td><td>L</td></tr>
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Table 3. Fuzzy rules base

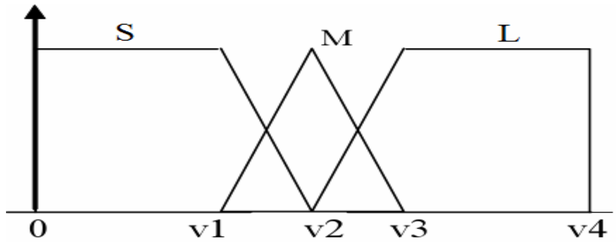


Fig.7. membership functions for output magnitude controller

IV. Speed Estimation with MRAS

A linear state observer for the rotor flux can then be derived as follows by considering the mechanical speed as a constant parameter since its variation is very slow in comparison with the electrical variables.

The symbol ˆ denotes an estimated quantity.

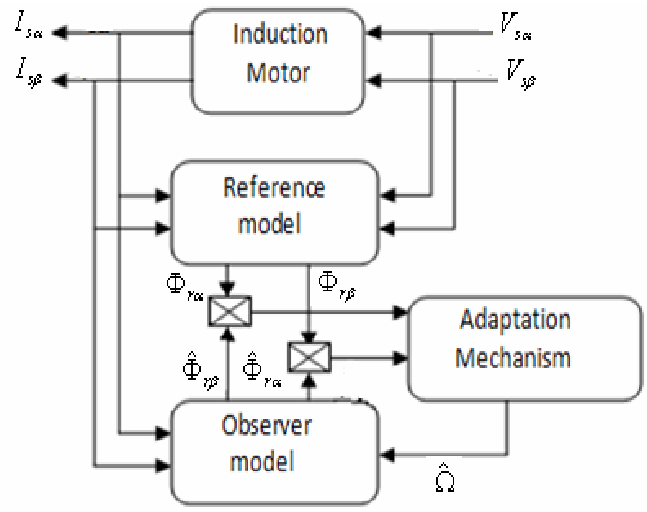


Fig.8. Adaptive observer structure

Since the reference model doesn't depend on the rotation speed, it allows to calculate the components of rotor flux from the equations of the stator voltage:

$$\begin{aligned} \frac{d\Phi_{r\alpha}}{dt} &= \frac{1}{a}\left(V_{s\alpha} - R_s I_{s\alpha} - \frac{1}{\delta}\frac{dI_{s\alpha}}{dt}\right) \\ \frac{d\Phi_{r\beta}}{dt} &= \frac{1}{a}\left(V_{s\beta} - R_s I_{s\beta} - \frac{1}{\delta}\frac{dI_{s\beta}}{dt}\right) \end{aligned} \tag{10}$$

With

$$\delta = \frac{1}{\sigma L_s}, \quad a = \frac{M}{L_r} \qquad k = \frac{R_r}{L_r}$$

The observer model uses the speed of rotation in its equations and permits to estimate the components of rotor flux:

$$\begin{aligned} \frac{d\hat{\Phi}_{r\alpha}}{dt} &= -k.\Phi_{r\alpha} - p\hat{\Omega}.\Phi_{r\beta} + k.M.I_{s\alpha} \\ \frac{d\hat{\Phi}_{r\beta}}{dt} &= -k.\Phi_{r\beta} + p\hat{\Omega}.\Phi_{r\alpha} + k.M.I_{s\beta} \end{aligned} \tag{11}$$

The adaptation mechanism compares the two models and estimates the speed of rotation by an integral proportional regulator. Using Lyapounov stability theory, we can construct a mechanism to adapt the mechanical speed from the asymptotic convergence's condition of the state variables estimation errors.

$$\hat{\Omega}=K_p.(\hat{\Phi}_{r\alpha}\Phi_{r\beta}-\Phi_{r\alpha}\hat{\Phi}_{r\beta})+K_i\int(\hat{\Phi}_{r\alpha}\Phi_{r\beta}-\Phi_{r\alpha}\hat{\Phi}_{r\beta})dt \quad (12)$$

K_p And K_i are positive gains.

V. SPEED CONTROL METHODS

A. PI Fuzzy logic controller

The block diagram of the PI Fuzzy controller is shown in fig. 9, where the variables K_p, K_i and B are used to tune the controller.

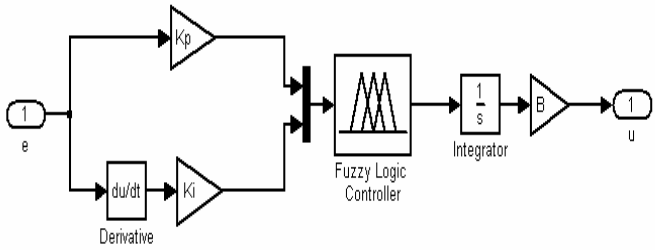


Fig.9. PI Fuzzy controller

One possible initial rule base, that can be used in drive systems for a fuzzy logic controller, consist of 49 linguistic rules, as shown in Table 4, and gives the change of the output of fuzzy logic controller in terms of two inputs: the error (e) and change of error (de). The membership functions of these variables are given in Fig.10:

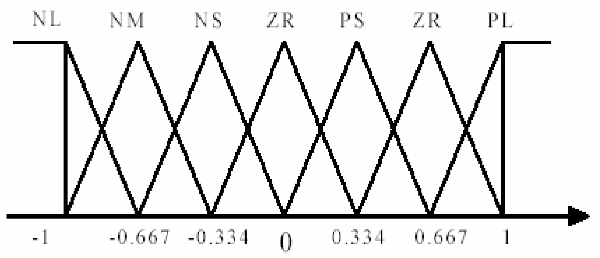


Fig. 10. Membership functions

In Table 4, the following fuzzy sets are used: NL negative large, NM negative medium, NS negative small, ZR zero, PS positive small, PM positive medium and PL positive large. For example, it follows from Table 2 that the first rule is:

IF **e** is NL and **de** is NL then **du** is NL

E/dE	NL	NM	NS	ZR	PS	PM	PL
PL	ZR	PS	PM	PL	PL	PL	PL
PM	NS	ZR	PS	PM	PL	PL	PL
PS	NM	NS	ZR	PS	PM	PL	PL
ZR	NL	NM	NS	ZR	PS	PM	PL
NS	NL	NL	NM	NS	ZR	PS	PM
NM	NL	NL	NL	NM	NS	ZR	PS
NL	NL	NL	NL	NL	NM	NS	ZR

Table 4.Fuzzy rules base

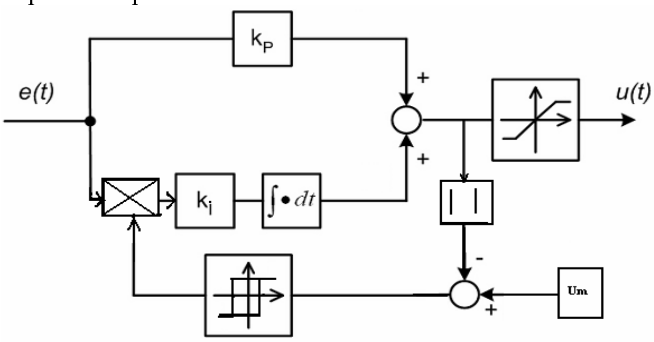
The linguistic rules are in the form of IF-THEN rules and take form: IF (e is X and de is Y) then (du is Z), where X, Y, Z are fuzzy subsets for the universe of discourse of the error, change of error and change of the output. For example, X can denote the subset NEGATIVE LARGE of the error etc. On every of these universes is placed seven triangular membership functions (fig.10). It was chosen to set these universes to normalized type for all of inputs and output. The range of universe is set to -1 to 1.

B. PI anti-windup

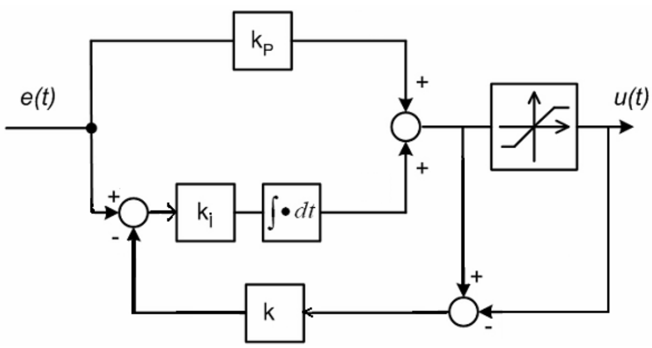
A PI controller provides a control action composed by a linear combination of the position error and it's integral.

$$u = Kp.e(t) + Ki.\int e(t)dt \quad (13)$$

When the error is very high and remains for a long time always positive (or negative), situation very common in variation of speed, integrating it the action provided by the second term of the equation (13) prevails and the danger of saturating the actuators, asking for performance they can not provide, rises very much. The saturation of the system introduces a non-linearity which deteriorates the control action, generating unforeseen oscillations in the system that can be easily go to instability. To resolve this problem the integral action must be limited over a decided error threshold. Various such control schemes exist in literature [18], one is shown in Fig.11. A PI anti-windup controller is not a real adaptive controller; the values of the proportional and integral gain are constant, but the anti-windup device allows to improve the performance in case of saturation.



(a)



(b)

Fig.11. PI anti-windup (a) approach 1 (b) approach 2

VI. SIMULATION RESULTS

The induction motor used for the simulations has the following parameters:

Rs=0.85Ω, Rr=0.16 Ω, Ls=0.16H, Lr=0.023H, M=0.058H, N=1440rpm, V=220V, J=0.05Kg.m^2, p=2.

An inverter switching frequency of 10 KHz was used.

The dynamic responses of torque, stator flux, stator phase current and speed for the starting process with [10 →-10] Nm load torque applied at 0.5s are shown in figure from 12 to 16 respectively.

To test the robustness of the sensorless speed control proposed, we applied a changing of the speed reference from 100rad/s to -100rad/s at 0.8s. Operate as a low speed between ±10rad/s is presented. It also presents several speed controllers in order to choose the best. The responses of the various regulators, the error between the reference and the estimated speed (input signal of the regulator) and the applied controls (output signal of the regulator) are shown in figure from 17 to 20 respectively, then for the low-speed operation in figure from 21 to 23 respectively.

A. Torque control mode

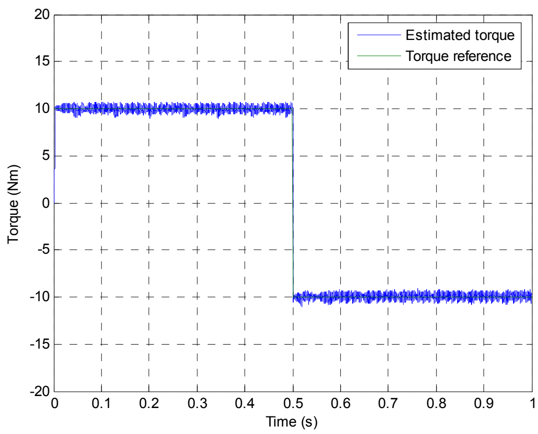


Fig. 12. Electromagnetic torque response

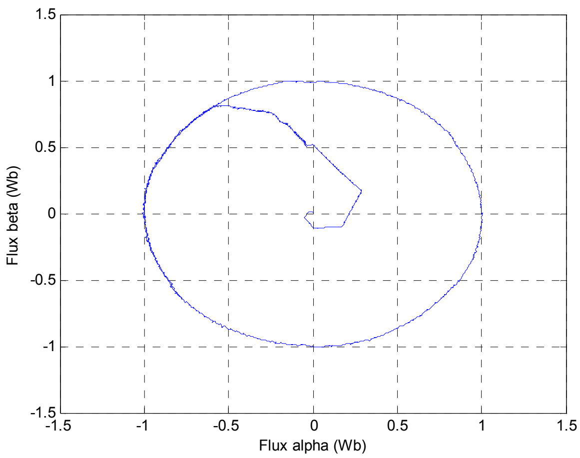


Fig.13. Stator flux trajectory

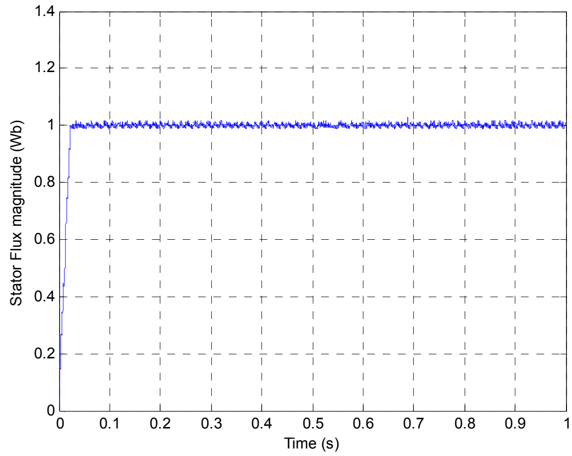


Fig.14. Stator flux magnitude

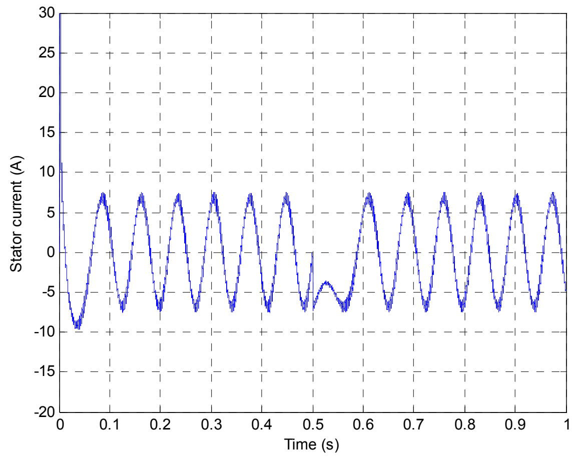


Fig.15. Stator phase current

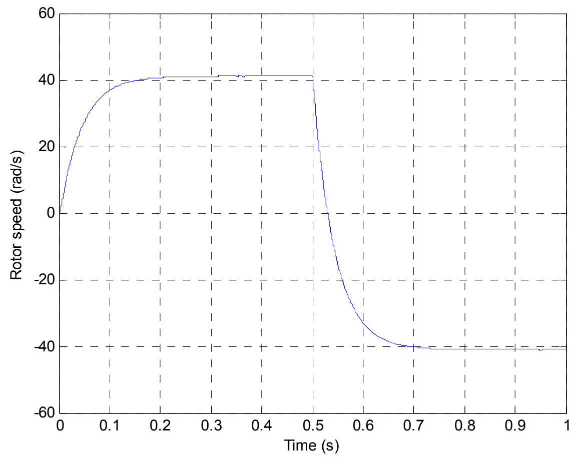


Fig.16. Estimated rotor speed

These figures show the good performance of the DTFC based fuzzy logic: the flux and torque are very good dynamic and stator phase current, torque and flux ripple is reduced remarkably.

B. Control of speed

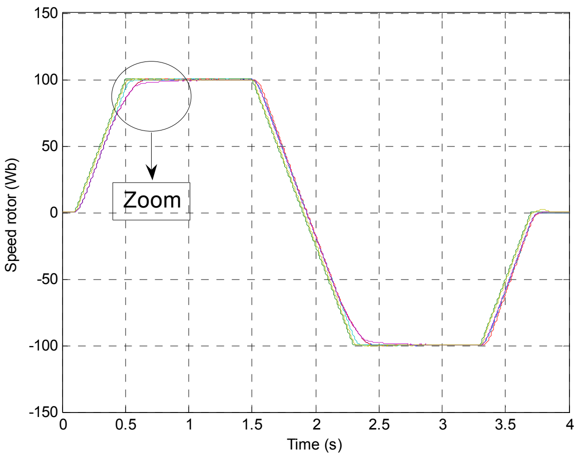


Fig.17. Estimated rotor speed

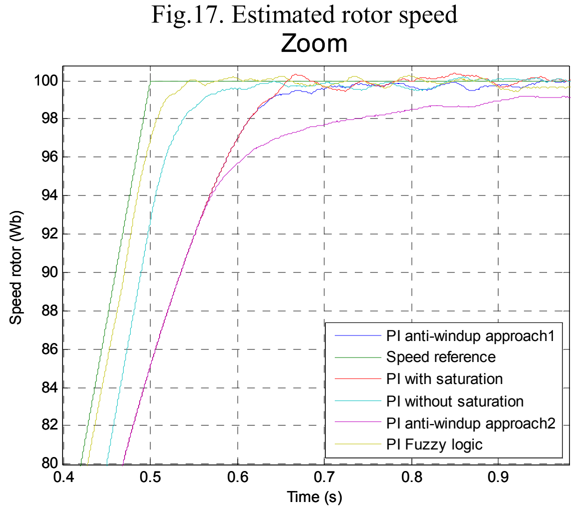


Fig.18. Zoom of speed response

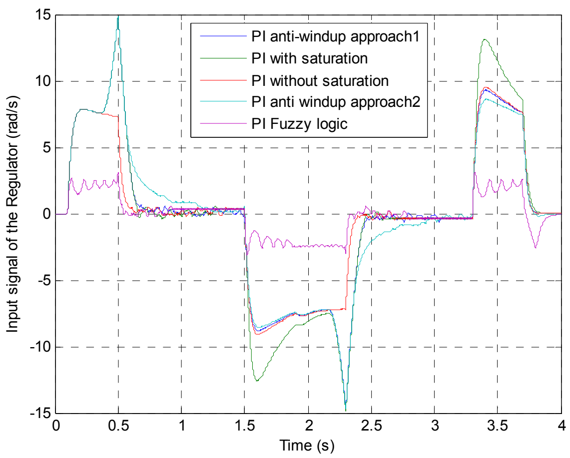


Fig.19. Input signal of the regulator

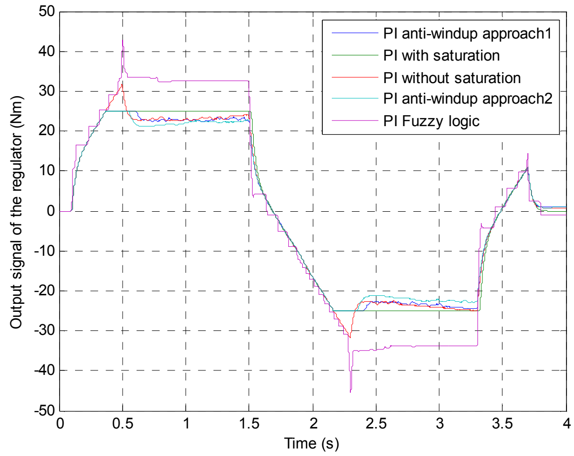


Fig.20. Output signal of the regulator

Figure 17 shows the speed transition from 100 rad/s to -100 rad/s with rated torque load. Estimated speed follows the reference speed closely.

Figure 18 shows that the PI fuzzy controller presents a fast response of estimated speed, followed by the PI without saturation while the PI anti-windup approach 2 is slower but not overrun. The figure 19 shows that amplitude of speed error is less with the PI fuzzy logic controller. The PI anti-windup approach 2 regulator, limit the command applied to system (figure 20).

C. Operation at low speed

The following figures illustrate the simulation results of the process of speed estimation with a reference equal to ±10rad/s. We can see that the speed follow perfectly the speed reference. Also with the PI fuzzy logic controller, the estimated speed does not follows the reference speed correctly and present the overtaking.

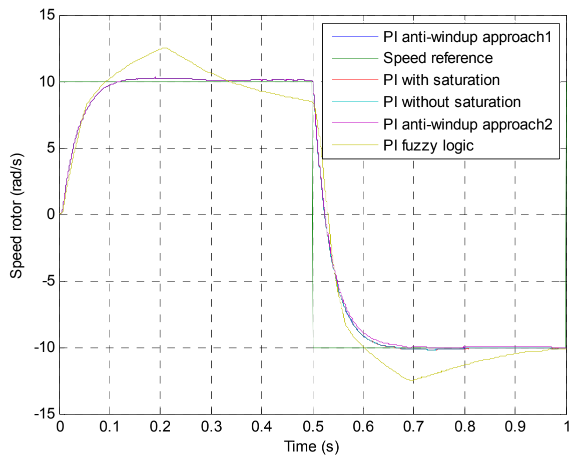


Fig. 21. Estimated rotor speed

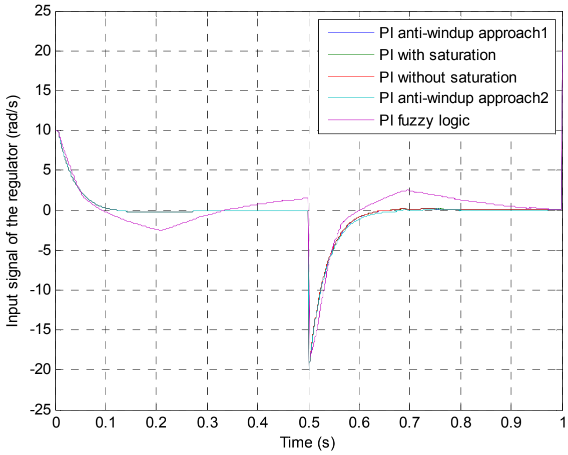


Fig.22. Input signal of the regulator

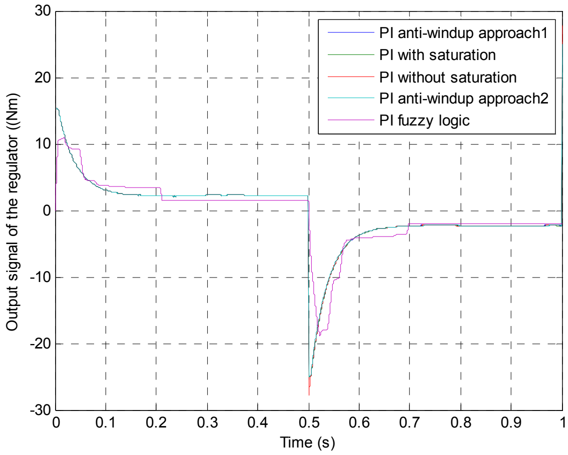


Fig.23. Output signal of the regulator

VII. Conclusion

In this paper, we have shown that, using a fuzzy logic controller associated with direct torque and flux control strategy, a fast dynamic and weak ripple have been obtained. Fuzzy logic controller applied to switching table, therefore, choosing voltage vectors is done with more accuracy. In this controller, torque error, flux error and also the position of stator flux are as inputs and the output of it is a suitable voltage vector which should apply to the motor. In this paper to reduce the number of rules and also increase controller's speed, we use particular mapping for the stator flux position. By applying this controller not also the quality of system keeps but also its speed increases.

The estimated speed follows the reference speed closely even at low speed. The comparison between different types of speed regulator shows that the PI fuzzy logic regulator is preferred when a fast speed is desired of the system, while the PI anti-windup regulator is preferred to limit the command and avoid saturation of the system.

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Appendix

Rated speed N	1440 rpm
Rated voltage V	220 V
Stator resistance Rs	0.85 Ω
Rotor resistance Rr	0.16 Ω
Stator inductance Ls	0.160 H
Rotor inductance Lr	0.023 H
Mutual inductance M	0.058 H
Motor-load inertia J	0.050 $kg.m^2$
Number of pole pairs p	2

Table 5. Induction motor data