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Intelligent Control for Torque Ripple Minimization in Combined Vector and Direct Controls for High Performance of IM Drive

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Abstract – In Conventional Combined Vector and Direct Controls (VC-DTC) of induction motor, stator current is very rich in harmonic components. It leads to high torque ripple of induction motor in high and low speed region. To solve this problem, a control method based on the concept of fuzzy logic approach is used. The control scheme proposed uses stator current error as variable. Through the fuzzy logic controller rules, the choice of voltage space vector is optimized and then torque and speed are controlled successfully with a less ripple level in torque response, which improve the system's performance. Simulation results trough MATLAB/SIMULINK® software gave results that justify the claims.

Keywords: Combined vector and direct controls, Fuzzy control approach, Induction motor, Torque ripple minimization

1. Introduction

In recent decades, induction motors had been widely used in industrial field due to their reliability, low cost, and efficiency in comparison with DC motors which suffer from the drawbacks of the brushes-collector, corrosion and necessity of maintenance. However, induction motors are considered as nonlinear, multivariable and highly coupled systems [1, 2]. For this reason, induction motors have been used especially in closed-loop, for adjustable speed application [3]. With the recent advance of powerful microprocessor, such as the Digital Signal Processors (DSP), the implementation of complex techniques for high precision torque and speed control of induction motors becomes possible [4].

Vector control introduced in the early 1970 allowed a considerable increase of dynamic performance of the induction motors (IM) and had been adopted as standard solution for industrial problems related to induction motor drive [5, 6]. The aim of vector control is to make the drive equivalent to DC motor drives by using the slip frequency to achieve the orientation [7]. Many vector control schemes have been developed in [8]. However, in all these schemes both the torque and the rotor flux are controlled by the stator current which is decomposed into two components.

Investigation on motor characteristics, including torque, speed and current, under the effect of the rotor resistance has been presented in [9, 10] and many solutions have been proposed to increase the robustness of the drive [11, 12].

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To improve the performance of the torque and speed control, the Direct Torque Control found great success. It provides a very rapid, precise torque response, and lower parameter sensibility without a complex field orientation block and current regulation [13, 14]. The Direct Torque Control was introduced in the first time in [15] by Takahashi. It consists of a pair of hysteresis comparators, torque and flux calculator, a lookup table, and a voltage-source inverter [16]. Still, major problems are usually related to this drive such as stator resistance variation and then inaccuracy in flux estimation [17]. Induction motor performance studies concerning the effect of this parameter and its compensation were subject of several previous works [18, 19].

In order to join both of Vector and Direct torque control performances: swiftness and accuracy, a new scheme has been developed and proposed in [20] and [21], based on fundamental common basis. The main innovative of this control is to use a pair of hysteresis comparators to control Torque and flux trough stator current and lookup table used to drive voltage source inverter. Although the superiority of this method over either the vector control method or direct torque control, it still has some drawbacks that can be summarized in the following points: High current and torque ripple, Variable switching frequency with operating conditions and current distortion.

In this paper we present an improved combined vector and direct torque control by incorporating fuzzy logic. The fuzzy controller proposed uses stator current error as variable, through the fuzzy rules, the choice of voltage space vector is optimized and then the torque and speed are controlled successfully with a less ripple level in torque response and current. Simulation results obtained for the proposed control show the efficiency of the proposed fuzzy scheme.

This paper is organized as follows. The equations of Induction Motor model are developed in Section 2, while Section 3 describes a simple review of vector and direct torque control strategies. In Section 4, the conventional combined vector and direct torque control is presented and the improved structure proposed in this work is presented in section 5. In Section 6, simulation results of the improved control described in this work in comparison with the conventional control are shown and discussed.

2. Induction Motor Dynamic Model

The induction motor model, described by using a space vector notation and written in *(d, q)* reference frame, rotating at the synchronous speed ω_s is given by the following equations [22]:

$$\begin{aligned} v_{sd} &= R_s i_{sd} + \frac{d\Phi_{sd}}{dt} - \omega_s \Phi_{sq} \\ v_{sq} &= R_s i_{sq} + \frac{d\Phi_{sq}}{dt} + \omega_s \Phi_{sd} \end{aligned} \tag{1}$$

$$\begin{aligned} v_{rd} &= 0 = R_r i_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_r \Phi_{rq} \\ v_{rq} &= 0 = R_r i_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_r \Phi_{rd} \end{aligned} \tag{2}$$

where v_{sd} and v_{sq} are the (*d, q*) axis stator voltages, (i_{sd}, i_{sq}) and (i_{rd}, i_{rq}) are respectively the (*d, q*) stator and rotor axis current. ω_s and ω_r are respectively reference frame and the slip speed. (Φ_{sd}, Φ_{sq}) and (Φ_{rd}, Φ_{rq}) represent the (*d, q*) axis stator and rotor fluxes, they can be described by the following equations:

$$\begin{aligned} \Phi_{sd} &= L_s i_{sd} + M i_{rd} \\ \Phi_{sq} &= L_s i_{sq} + M i_{rq} \end{aligned} \tag{3}$$

$$\begin{aligned} \Phi_{rd} &= M i_{sd} + L_r i_{rd} \\ \Phi_{rq} &= M i_{sq} + L_r i_{rq} \end{aligned} \tag{4}$$

where L_s and L_r are stator and rotor inductance, M is the mutual inductance.

The mechanical and the electromagnetic torque equations are given by:

$$T_e - T_l = J_\Delta \frac{d\omega}{dt} + f_r \omega \tag{5}$$

$$T_e = p\frac{M}{L_r}(\Phi_{rd} i_{sq} - \Phi_{rq} i_{sd}) \tag{6}$$

where T_l describes the load torque, ω is the rotor speed, f_r is the friction coefficient, J_Δ represents the total inertia and p is the number of pole pairs.

The induction motor can also be described by a state model. In literature of electrical drive, many models are proposed; it can be chosen according to the theory of the drive adopted. We present by the following system, the state model used to design the drive:

$$\begin{aligned} \dot{X} &= A.X + B.U \\ Y &= C.X \end{aligned} \tag{7}$$

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

$$X^T = (i_{sd}\ i_{sq}\ \Phi_{rd}\ \Phi_{rq}) \ ; \ U = \begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} \ ; \ Y = \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix}$$

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

$$B = \begin{pmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \ ; \ C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

With σ is the total leakage factor, it is given by the following expression:

$$\sigma = 1 - \frac{M^2}{L_s L_r}.$$

T_s and T_r represent respectively the stator and the rotor time constants, they are given by the expressions below :

$$T_s = \frac{L_s}{R_s} \quad \text{and} \quad T_r = \frac{L_r}{R_r}.$$

3. Vector and Direct Torque Control Review

3.1 Vector control

The main objective of the vector control of induction motors is, as in DC machines, to independently control the torque and the flux; this is done by using a *d-q* rotating reference frame synchronously with the rotor flux space vector [23].

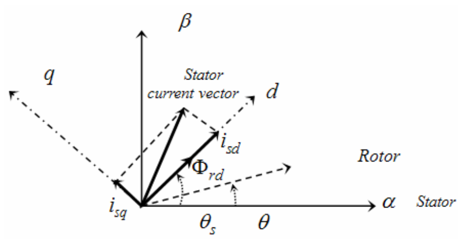

Fig. 1. Reference frames and space vector representation.

θ_s and θ are respectively *d-q* Reference frame and the rotor position. Considering the orientation in Fig. 1 we have:

$$\Phi_{rd} = \Phi_r \text{ and } \Phi_{rq} = 0 \quad (8)$$

where Φ_r is the total flux according to the axis *d*.

It can be seen that if the rotor flux is kept constant by the direct axis stator current, the torque can be controlled by controlling the *q*-axis current. From the state model, we have:

$$\begin{aligned} v_{sd} &= \sigma L_s \frac{di_{sd}}{dt} + R_{sr} i_{sd} - \sigma L_s \omega_s i_{sq} - \frac{M}{L_r^2} R_r \Phi_r \\ v_{sq} &= \sigma L_s \frac{di_{sq}}{dt} + R_{sr} i_{sq} + \sigma L_s \omega_s i_{sd} + \frac{M}{L_r} \omega \Phi_r \end{aligned} \quad (9)$$

If the decoupling method is implemented, the voltage equations become:

$$v_{sd} = v_{sd}^* - e_{sd} = \sigma L_s \frac{di_{sd}}{dt} + R_{sr} i_{sd} \quad (10)$$

$$v_{sq} = v_{sq}^* - e_{sq} = \sigma L_s \frac{di_{sq}}{dt} + R_{sr} i_{sq} \quad (11)$$

where:

$$R_{sr} = R_s + \left(\frac{M}{L_r}\right)^2 R_r ; \quad e_{sd} = \sigma L_s \omega_s i_{sq} + \frac{M}{L_r^2} R_r \Phi_r$$

$$e_{sq} = -\sigma L_s \omega_s i_{sd} - \frac{M}{L_r} \omega \Phi_r$$

e_{sd} and e_{sq} represent the compensation terms, if they are considered, the dynamic of the stator current can be represented by simple linear first order differential equations. Therefore, it is possible to control the current components by a simple Proportional Integral corrector.

Fig. 2 shows the vector control scheme:

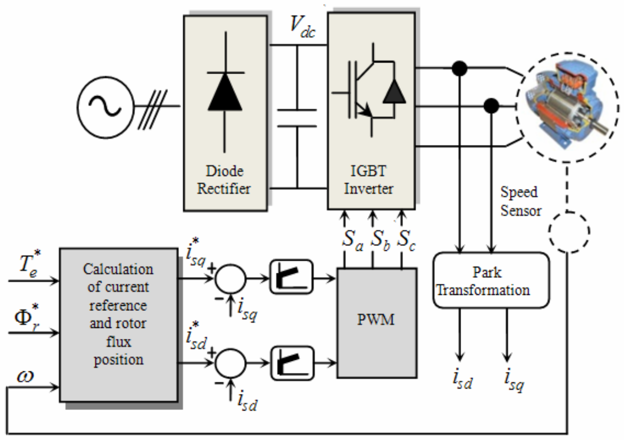

Fig. 2. Vector Control Scheme.

3.2 Direct torque control

In Direct Torque Control Drive, both the electromagnetic torque and flux are controlled directly by applying one of the six active inverter voltage vectors. The following equations of the induction motor can explain the principle of this drive.

Using the equations of the stator and the rotor voltages we have:

$$\begin{aligned} v_s &= R_s i_s + \frac{d\Phi_s}{dt} \\ v_r &= R_r i_r + \frac{d\Phi_r}{dt} - j\omega\Phi_r \end{aligned} \quad (12)$$

where v_s and v_r are the stator voltages, (i_s, i_r) and are respectively the stator and rotor current. (Φ_s , Φ_r) represent stator and rotor fluxes.

From the flux equations, the rotor current can be expressed as:

$$i_r = \frac{1}{\sigma}\left(\frac{\Phi_r}{L_r} - \frac{M}{L_s L_r}\Phi_s\right) \quad (13)$$

Substituting (13) in (12) we obtain:

$$\begin{aligned} v_s &= R_s i_s + \frac{d\Phi_s}{dt} \\ \frac{d\Phi_r}{dt} &+ \left(\frac{1}{\sigma T_r} - j\omega\right)\Phi_r = \frac{L_m}{L_s}\frac{1}{\sigma T_r}\Phi_s \end{aligned} \quad (14)$$

From the system described by (14) we conclude:

- Stator voltage v_s controls the stator flux Φ_s
- The rotor flux Φ_r dynamic is controlled by Φ_s

In these conditions the electromagnetic torque can be expressed as:

$$T_e = p\frac{M}{\sigma L_s L_r}\Phi_s \Phi_r \sin\alpha \quad (15)$$

where α denotes the angle between the stator and the rotor flux. The derivative of equation (15) can be approached to the following expression [20]:

$$\frac{dT_e}{dt} = p\frac{M}{\sigma L_s L_r}\Phi_s \Phi_r \frac{d\alpha}{dt}\sin\alpha \quad (16)$$

Expression (16) shows that the variation of α controls the Torque dynamic by applying one of the six inverter voltage vectors. In a short interval Δt the stator flux variation can be expressed as:

$$\Delta\Phi_s \approx v_s \Delta t \quad (17)$$

One of the six inverter voltage vectors can be chosen appropriately to control the stator flux position and its modulus, indirectly the rotor flux following the variation of stator flux during Δt since the two vectors are related by (14).

Table 1 shows the switching table which can be applied in DTC drive and Fig. 3 shows the DTC scheme:

Table 1. Switching table of DTC drive

Sector		1	2	3	4	5	6
$\Delta\Phi_s$ ↑	ΔT_e ↑	v_2	v_3	v_4	v_5	v_6	v_1
	ΔT_e=0	v_7	v_0	v_7	v_0	v_7	v_0
	ΔT_e ↓	v_6	v_1	v_2	v_3	v_4	v_5
$\Delta\Phi_s$ ↓	ΔT_e ↑	v_3	v_4	v_5	v_6	v_1	v_2
	ΔT_e=0	v_0	v_7	v_0	v_7	v_0	v_7
	ΔT_e ↓	v_5	v_6	v_1	v_2	v_3	v_4

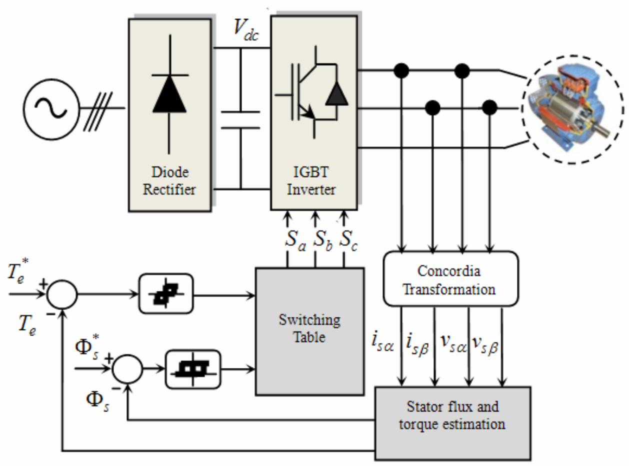

Fig. 3. Direct Torque Control Scheme.

4. Conventional Combined Vector Control and Direct Torque Control

In this part, we present the basis of combined Vector Control and Direct Torque Control developed in [20] and [21]. As shown in section 3 for the vector control, the rotor flux and the electromagnetic torque can be approximated to the following systems :

$$\begin{cases}\Phi_r = \lambda_d i_{sd} \\ T_e = \lambda_q i_{sq}\end{cases} \Rightarrow \begin{cases}\Phi_r \propto i_{sd} \\ T_e \propto i_{sq}\end{cases} \Rightarrow \begin{cases}\Delta\Phi_r \propto \Delta i_{sd} \\ \Delta T_e \propto \Delta i_{sq}\end{cases} \quad (18)$$

where λ_d and λ_q depend on the parameters of induction motor. For the DTC drive. $\Delta\Phi_s$ in a switching period inverter can be decomposed into two components :

The radial component $\Delta\Phi_{sf}$. This component controls the level of the stator flux

The tangential component $\Delta\Phi_{st}$. This component controls the angle of flux rotation.

Fig. 4 shows the rotation stator flux vector from Φ_s to Φ_{s1} in a switching inverter period:

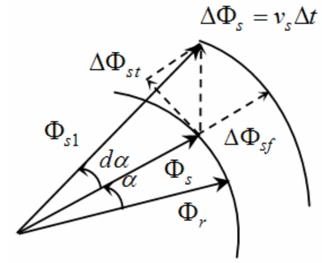

Fig. 4. Stator flux vector rotation in a switching intverter period

In this condition, the variation of the electromagnetic torque can be expressed as [20]:

$$\Delta T_e = k\Phi_r \left(\Phi_{s1}\sin(\alpha + \Delta\alpha) - \Phi_s \sin\alpha\right) \quad (19)$$

where k depends on the induction motor parameters. With a good approximation:

$$\sin(\alpha + \Delta\alpha) = \sin\alpha + \cos\alpha \sin\Delta\alpha \quad (20)$$

And:

$$\sin\Delta\alpha = \frac{\Delta\Phi_{st}}{\Phi_s} \quad (21)$$

From Fig. 4, the new flux Φ_{s1} can be described by:

$$\Phi_{s1} = \Phi_s + \Delta\Phi_{st} \quad (22)$$

Substituting (20), (21) and (22) in (19) the electromagnetic torque variation may be given by [20]:

$$\Delta T_e = k\Phi_s \Delta\Phi_{st} \cos\alpha \quad (23)$$

We conclude then:

$$\Delta T_e \propto \Delta\Phi_{st} \quad (24)$$

Considering the Fig. 4, the level variation of the stator flux is given by:

$$\Delta\Phi_s = \Delta\Phi_{sf} \quad (25)$$

In connection with the system (14), the level variation of the rotor flux is:

$$\Delta\Phi_r = \Delta\Phi_{sf} \quad (26)$$

Referring to the system (18), we obtain the relation between the radial component, tangential component and the stator current which is given by:

$$\begin{cases} \Delta\Phi_{sf} \propto \Delta i_{sd} \\ \Delta\Phi_{st} \propto \Delta i_{sq} \end{cases} \quad (27)$$

figure below shows the conventional combined vector control and Direct torque control :

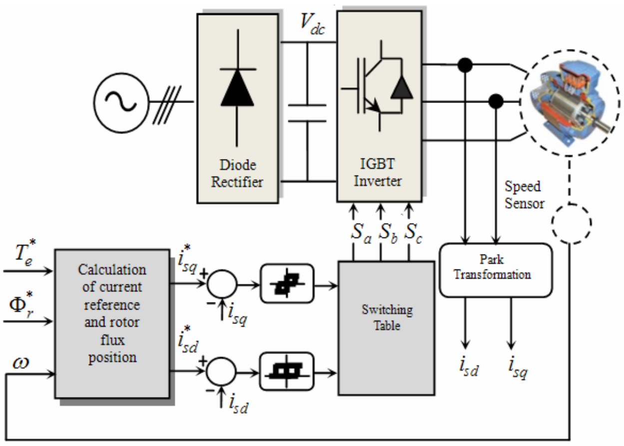

Fig. 5. Combined Vector Control and Direct Torque Control Scheme

5. Improved Combined Vector Control and Direct Torque Control

Recently, Fuzzy logic was found a particular attention and becomes popular and useful to solve nonlinear control problems or when the plant model is unknown or difficult to build [24]. In the case of Induction motor, Fuzzy logic techniques have been proposed in different error minimization applications: Speed control, online tuning of parameters variation and other applications.

To obtain an improved combined vector and Direct torque control during start-up or during changes in the reference flux and torque, a fuzzy logic controller is proposed and introduced to replace the switching table for more advantages [24-26]: Torque ripple minimization, current distortion reduction and switching frequency stabilization.

5.1. Control variable description

As desipated in Fig. 6, the fuzzy controller has been developed in order to have three inputs which are the stator current errors and the position θ_s and one output considered as the three commutation state S_a, S_b, S_c.

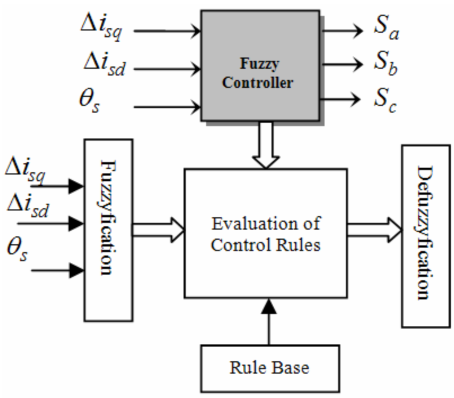

Fig. 6. Fuzzy Controller Structure

The fuzzy controller is composed of three blocks: Fuzzyfication, rules base, and Defuzzyfication. For this purpose, a Mamdani type fuzzy logic system will be used. The variables defined for the fuzzy controller are distributed into fuzzy sets, with the number of each one is defined in order to obtain high control with optimized number of rules [27]. For the first input which is the error of stator current Δi_{sq}, it is defined as difference between the reference value i_{sq}^* and the measured component, this error can be expressed as :

$$\Delta i_{sq} = i_{sq}^* - i_{sq} \quad (28)$$

With the reference current i_{sq}^* is given by the expression obtained from the control algorithm:

$$i_{sq}^* = \frac{L_r}{pM\Phi_r^*} T_e^* \quad (29)$$

In order to reduce the torque variation which is traduced by less ripple, with action on the i_{sq} component, the universe of discourse associated to error Δi_{sq} is divided into three fuzzy sets described by three membership functions: P (positive), Z (zero) and N (negative). The membership functions used are triangular and shown in Fig. 7(a).

For the second input of the fuzzy controller used for flux control, it is considered as error between the reference component i_{sd}^{*} and the measured one, this error is given by:

$$\Delta i_{sd} = i_{sd}^{*} - i_{sd} \tag{30}$$

With the reference current i_{sd}^{*} given by the expression:

$$i_{sd}{}^{*} = \frac{1}{M}\Phi_r{}^{*} \tag{31}$$

For the universe of discourse of this input two membership functions were used to describe each fuzzy set: N (Negative) and P (Positive). The membership functions are shown in Fig. 7(b).

The third input is the stator flux position θ_s given by:

$$\theta_s = \int \omega_s = \int (\omega + \omega_r) = \theta + \int \frac{M}{T_r \Phi_r{}^{*}} i_{sq}{}^{*} \tag{32}$$

6 fuzzy sets are used to describe the universe of discourse of this input. The membership functions are given in Fig. 7(c).

The output variable of the fuzzy controller is the commutation state S_a, S_b, S_c. They are used to define the appropriate active inverter voltage vectors.

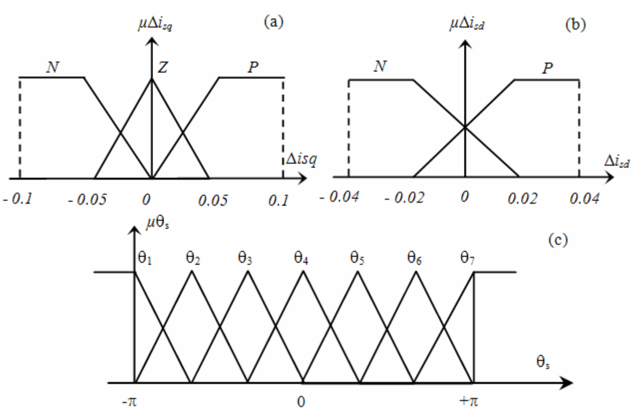

Fig. 7. Fuzzy controller input membership functions: (a) fuzzy membership of Δi_{sd}; (b) fuzzy membership of Δi_{sq}; (c) fuzzy membership of θ_s

5.2 Fuzzy rules for control

The rules supporting this system can be described using the state variables Δi_{sq} Δi_{sd} and θ_s and the commutation state variable s (S_a, S_b, S_c). In the case of the ith rule R_i, it can be written as:

R_i : if (Δi_{sq} is a_i), (Δi_{sd} is b_i), (θ_s is c_i) then (s is d_i)

Where the a_i, b_i, c_i and d_i represent the fuzzy sets. Based on the vector evolution shown in Fig. 8 we can formulate the rule bases of the fuzzy controller.

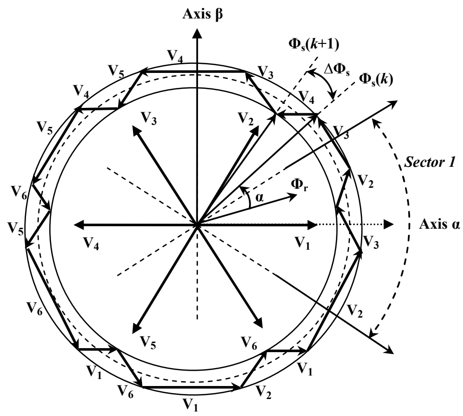

Fig. 8. Stator Vecor flux evolution according the applied inverter voltage vector.

Considering the case of the first sector, vectors v_2 and v_5 allow a fast evolution of electromagnetic torque but a slow evolution of the stator flux modulus, we can conclude than that through these vectors we can have a fast evolution of the tangential component $\Delta\Phi_{st}$ and slow evolution of the radial component $\Delta\Phi_{sf}$. In the other hand, vectors v_3 and v_6 can reverse the effect on the electromagnetic torque and flux, which is a slow evolution of the electromagnetic torque modulus and fast evolution of the stator flux. Using the measured stator currents component and based on the relation (27) we choose the appropriate stator voltage, for example in sector 2, for large increase in flux and large increase in torque vector v_3 is selected, and for large increase in flux with a small increase in torque vector v_0 is selected. With this process of reasoning we will have 42 rules and using deffezufication process, the output variable

θ_1

Δi_{sq} \ Δi_{sd}	P	N
P	v_5	v_6
Z	v_0	v_7
N	v_3	v_2

θ_2

Δi_{sq} \ Δi_{sd}	P	N
P	v_6	v_1
Z	v_7	v_0
N	v_4	v_3

θ_3

Δi_{sq} \ Δi_{sd}	P	N
P	v_1	v_2
Z	v_0	v_7
N	v_5	v_4

θ_4

Δi_{sq} \ Δi_{sd}	P	N
P	v_2	v_3
Z	v_7	v_0
N	v_6	v_5

θ_5

Δi_{sq} \ Δi_{sd}	P	N
P	v_3	v_4
Z	v_0	v_7
N	v_1	v_6

θ_6

Δi_{sq} \ Δi_{sd}	P	N
P	v_4	v_5
Z	v_7	v_0
N	v_2	v_1

θ_7

Δi_{sq} \ Δi_{sd}	P	N
P	v_5	v_6
Z	v_0	v_7
N	v_3	v_2

Fig. 9. Rules base of the fuzzy controller

s is determined adequately to have high control of the inverter.

The rules supporting this control are presented in the figure below :

The scheme of the improved combiend Vector Control and Direct Torque Control is presented in Fig. 10 :

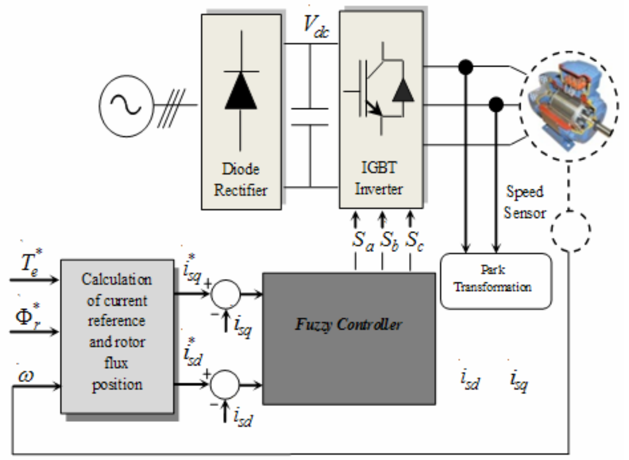

Fig. 10. Improved Combined Vector Control and Direct Torque Control scheme

6. Simulation Results & Discussions

Simulation studies for the proposed control scheme were performed by Matlab/Simulink® for an Induction Motor with the parameters shown in Tables 2. The dynamic performance of the drive system for different operating conditions has been studied with the uses of fuzzy controller and then compared with the conventional combined vector control and direct torque control (VC-DTC).

Table 2. Induction Motor Data

Components	NAME	Values
P	Rated Power	1kw
N	Rated Speed	1425 rpm
V	Rated Voltage	220 V
$R_{s,r}$	Stator and Rotor Resistance	6.8 Ω-5.43 Ω
$L_{s,r}$	Stator and Rotor Inductance	0.3973 H-0.3558 H
M	Mutual Inductance	0.3558 H
J	Motor Load-Inertia	0.02 Kg.m^2
p	Number of pole pairs	2

The dynamic responses of torque, stator current components, and stator phase current for the starting process with [6→-6] N.m at 2s and then [-6→3] N.m at 3.5s.

Figs. 11, 12 and 14 illustrate the high performance obtained with the improved combined vector and direct torque control. Since the fuzzy controller can provide

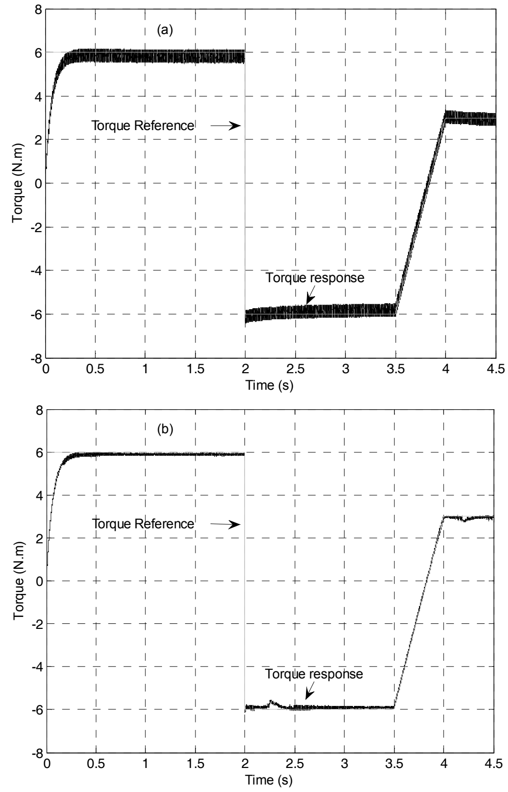

Fig. 11 Torque response: (a) conventional combined VC-DTC; (b) Improved combined VC-DTC

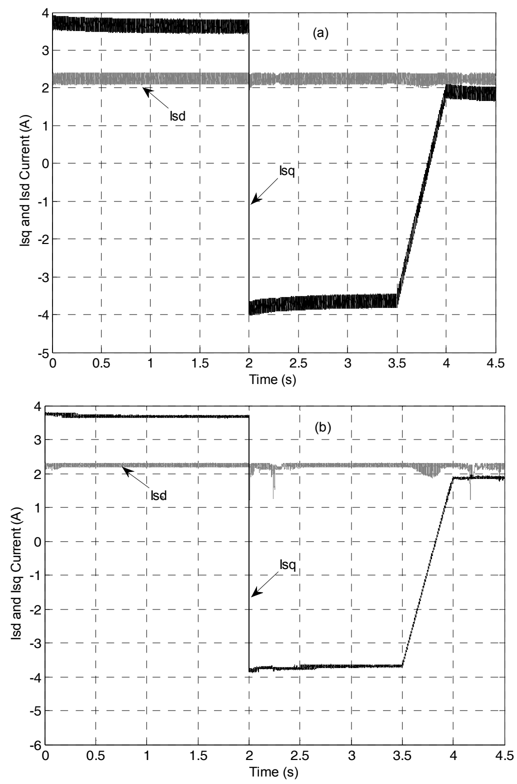

Fig. 12. Isd and Isq components: (a) conventional combined VC-DTC; (b) Improved combined VC-DTC

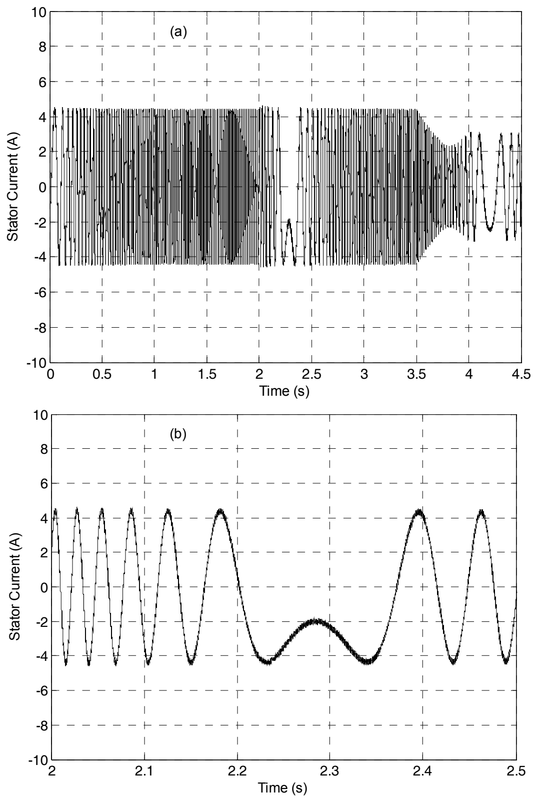

Fig. 13. Stator current in conventional combined VC-DTC: (a) stator current; (b) zoom on stator current

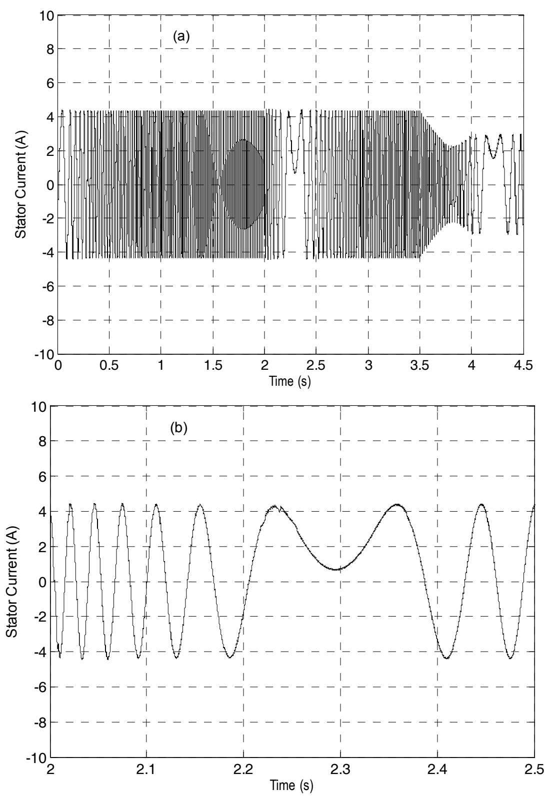

Fig. 14. Stator current in improved combined VC-DTC: (a) stator current; (b) zoom on stator current

suitable amplitude according to system operation station, the torque ripple was significantly reduced as shown in Fig. 10. And the distortion in both stator current component and stator phase current were substantially reduced as shown in Fig. 12 and 14 when using fuzzy controller in combined VC-DTC structure.

In order to evaluate further the proposed combined VC-DTC, a closed loop speed control with a simple IP controller is applied to the drive; we present also the results obtained with conventional combined VC-DTC for comparison. The drive was subject to step of speed

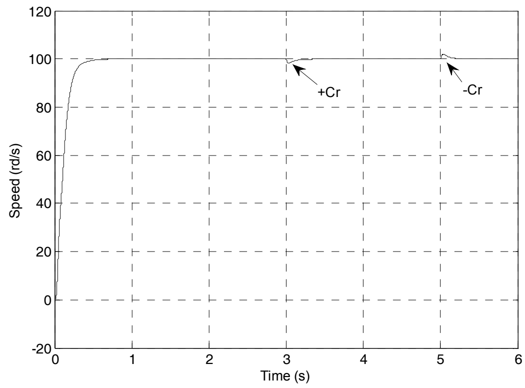

Fig. 15. Speed response in both conventional and proposed combined VC-DTC

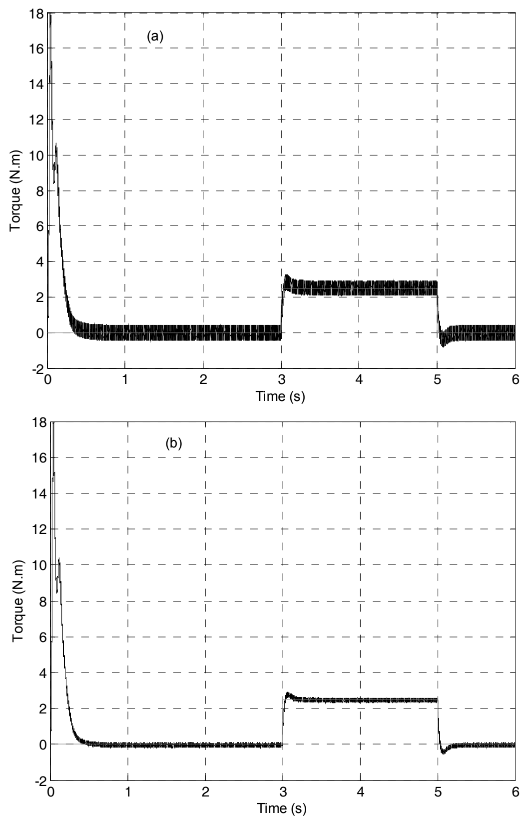

Fig. 16. Torque response: (a) conventional combined VC-DTC; (b) Improved combined VC-DTC

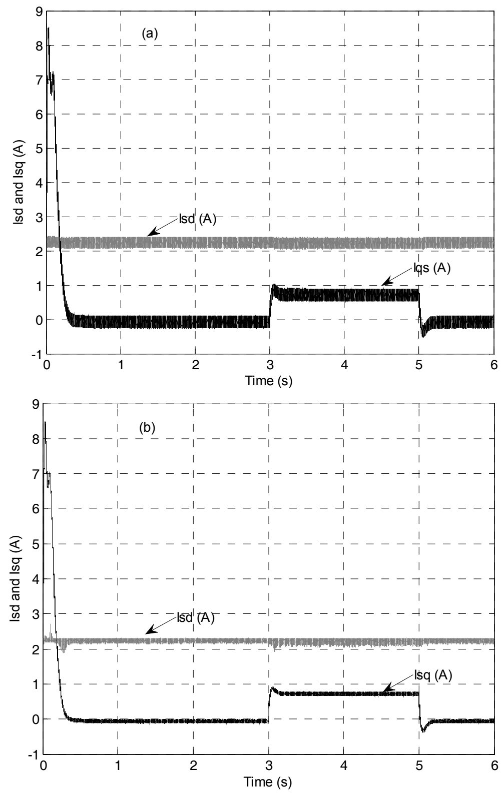

Fig. 17. Isd and Isq components: (a) conventional combined VC-DTC; (b) Improved combined VC-DTC

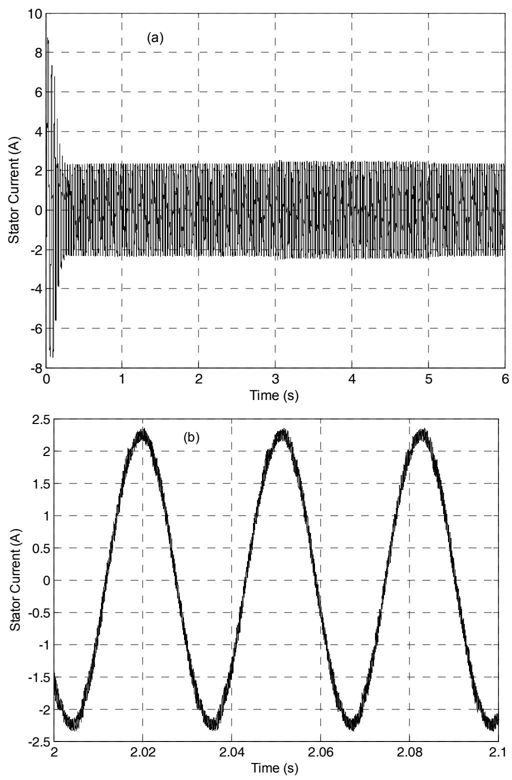

Fig. 18. Stator current in conventional combined VC-DTC: (a) stator current; (b) zoom on stator current

reference from [0→100] rd/s with introduction and rejection of load torque of 2.5N.m respectivly at 3s and 5s, figures below illustrate the results.

As shown, the proposed control provide high performance compared to conventional drive, it is seen that the proposed control system is capable of controlling the motor speed and torque as well as the conventional drive, with torque ripple minimization and reduced stator current distortion.

To test the robustness and the effeciency of the proposed drive, the induction motor was subject to low speed

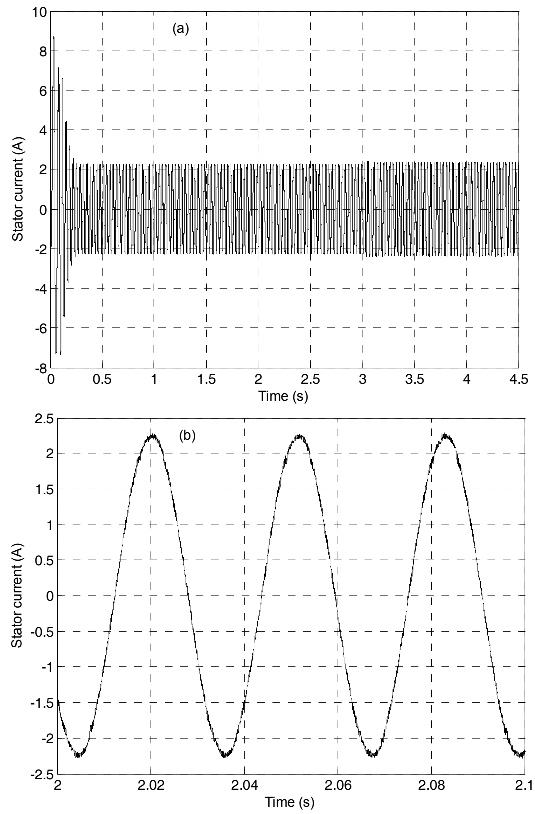

Fig. 19. Stator current in improved combined VC-DTC: (a) stator current; (b) zoom on stator current

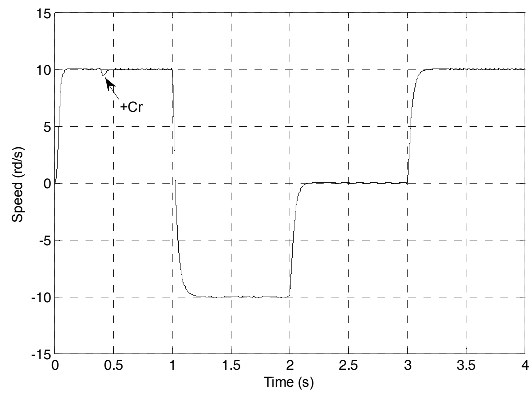

Fig. 20. Speed response in both conventional and proposed combined VC-DTC

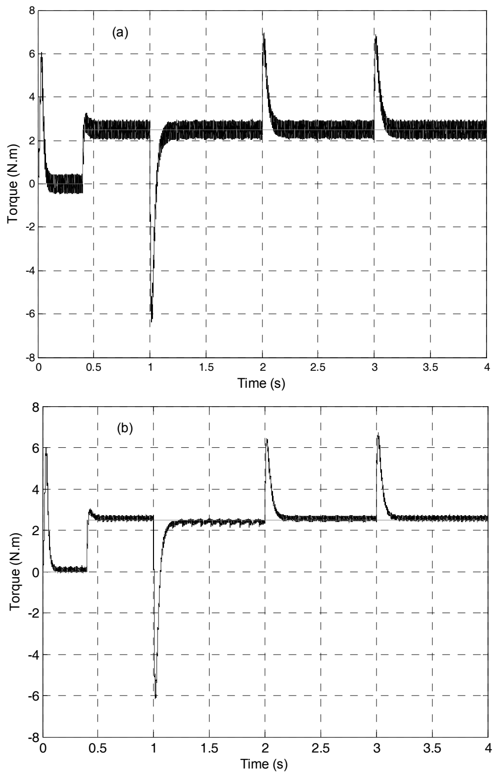

Fig. 21. Torque response: (a) conventional combined VC-DTC; (b) Improved combined VC-DTC

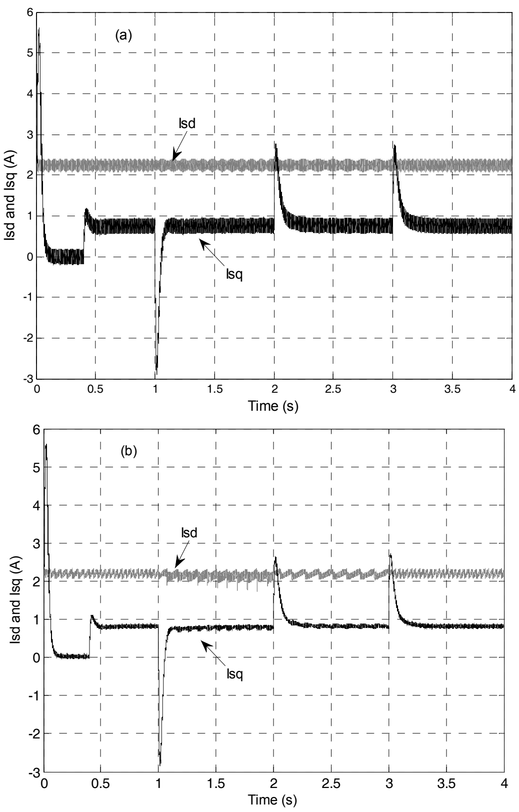

Fig. 22. Isd and Isq components: (a) conventional combined VC-DTC; (b) Improved combined VC-DTC

reference in order to illustrate the high performance obtained in this region which is a critical point of majority of the drives. Figures below illustrate the results of this invistigation:

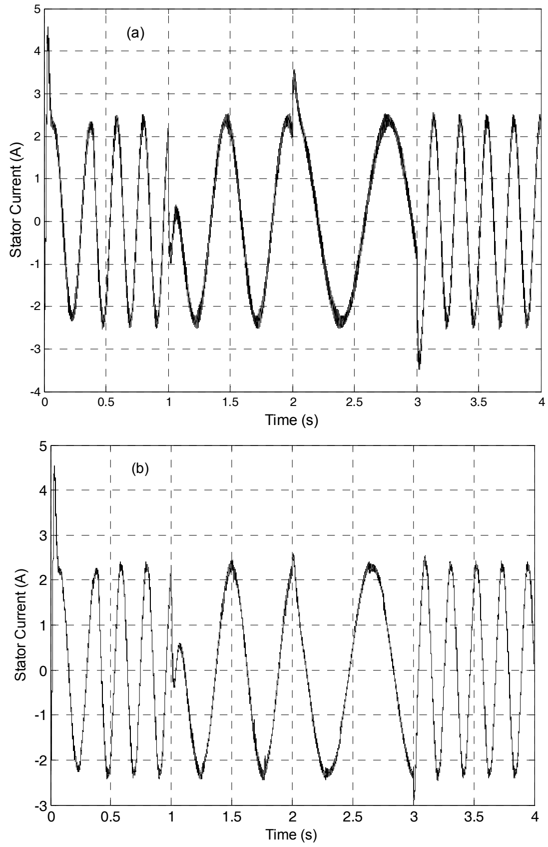

Fig. 23. Stator current: (a) conventional combined VC-DTC; (b) Improved combined VC-DTC

As shown in figures above even at low speed region, the proposed control ensures high performance drive compared with the conventional control. It was drawn that the improved combined vector control and direct torque control can effectively solve the shortcoming of the torque ripple in the conventional combined VC-DTC drive. The method provides an effective scheme for reducing motor torque ripple and noise in the low-speed operating conditions.

7. Conclusion

Conventional Combined vector control and Direct torque control is a simple and efficient method that can be applied to drive Induction Motor.However, there are some drawbacks associated to this drive such as the high torque ripple, current distortion and a non constant switching frequency. In this paper, a fuzzy controller for reducing torque ripple has been introduced in this drive. Simulation studies of this control illustrate the high performances obtained and the contribution added to this drive by reducing the torque ripple and improving the waveform of the stator current. The drive was improved also in low speed region wich is a critical point for the combined conventional Vector control and Direct torque control.

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