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Application of Fuzzy Logic for a Ripple Reduction Strategy in DTC Scheme of a PWM Inverter fed Induction Motor Drives

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Abstract—**This paper deals with the direct torque control (DTC) of the induction motor. This type of control allows decoupling control between the flux and the torque without the need for a transformation of coordinates. However, the DTC scheme has a high ripples for both electromagnetic torque and stator flux and a distortion of the stator current. To solve these problems, we have developed a new approach of DTC scheme making use of both the technique of space vector modulation (SVM) and the hysteresis comparator. The choice of the angle of the voltage vector applied to the motor is operated by a look-up table, while the voltage vector amplitude is calculated by an estimator based on fuzzy logic. Finally, the reference voltage vector will be synthesized using the space vector modulation. The main objective of this study is the reduction of electromagnetic torque ripples. Moreover, this approach allows the reduction of stator flux ripples as well as improving the form of the stator currents. Simulation results will illustrate the performance merits of our approach.**

Keywords—**Direct Torque Fuzzy Control, Fuzzy Logic, Induction Motor, Space Vector Modulation.**

I. INTRODUCTION

The direct torque control (DTC) of the induction machine was introduced in 1986 by I. Takahashi and M. Depenbrock [1]-[2]. The DTC is based on the orientation of the stator flux vector by direct action on the status of the converter switches. Depending on the position of the stator flux vector in one of six areas of the (α, β) plan, a look-up table allows the selection of the voltage vector to be applied to the machine.

The conventional DTC provide the fastest response of the torque and the stator flux at every moment. Contrary to the field oriented control, the DTC scheme is less dependent on machine parameters, since the value of the stator resistance is the only parameter of the machine used to estimate the stator flux [3].

The use of the hysteresis comparators is justified by their simplicity of implementation, their robustness, their speed unlimited and largely for their independence of parameter control.

The space vector pulse width modulation (SVM) uses a numerical algorithm to obtain a sequence of the inverter switches states to generate a voltage vector output approaching to the best, the reference voltage vector.

The three sinusoidal desired voltages at the output are represented by a single vector called reference voltage vector. We approximate this vector during each modulation period by acting on the inverter switching states [4].

A proposed algorithm aimed to improve the dynamic performance of the conventional DTC scheme is used in this paper. Indeed, the direct torque fuzzy control (DTFC) proposed in [5] is introduced with the aim of reducing the electromagnetic torque ripples, the stator flux ripples and improving the shape of the stator currents.

The angle of the reference voltage vector is chosen through a look-up table, while a fuzzy logic estimator is proposed to calculate the reference voltage vector amplitude leading to an optimal drive of both torque and flux to their required values.

II. MACHINE EQUATIONS

The dynamic behaviour of an induction machine is described by the following equations written in terms of space vectors in a stator reference frame [3], [6]:

$$\overline{V_s} = r_s \cdot \overline{i_s} + \frac{d\overline{\varphi_s}}{dt} \tag{1}$$

$$0 = r_r \cdot \overline{i_r} + \frac{d\overline{\varphi_r}}{dt} - j\omega_m \overline{\varphi_r} \tag{2}$$

$$\overline{\varphi_s} = L_s \cdot \overline{i_s} + M \cdot \overline{i_r} \tag{3}$$

$$\overline{\varphi_r} = L_r \cdot \overline{i_r} + M \cdot \overline{i_s} \tag{4}$$

Where r_s and r_r : represent the stator and rotor resistances, L_s, L_r and M :represent the self and mutual inductances, and ω_m :represent the rotor angular speed expressed in electrical radians.

The electromagnetic torque is expressed in terms of stator and rotor fluxes as:

$$C_{em} = p\frac{M}{\sigma L_s L_r}\left(\overline{\varphi_s} \cdot j\overline{\varphi_r}\right) \tag{5}$$

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Where p is the pole pair number. The elimination of $\overline{i_s}$ and $\overline{i_r}$ from (1) to (4) leads to the state variable form of the induction machine equations with stator and rotor fluxes as state variables:

$$\begin{bmatrix} \dfrac{d\overline{\varphi_s}}{dt} \\ \dfrac{d\overline{\varphi_r}}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{\sigma T_s} & \dfrac{M}{\sigma T_s L_r} \\ \dfrac{M}{\sigma T_r L_s} & j\omega_m - \dfrac{1}{\sigma T_r} \end{bmatrix} \cdot \begin{bmatrix} \overline{\varphi_s} \\ \overline{\varphi_r} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot \overline{V_s}$$

With $T_s = \dfrac{L_s}{r_s}$, $T_r = \dfrac{L_r}{r_r}$ and $\sigma = 1 - \dfrac{M^2}{L_s \cdot L_r}$

III. DIRECT TORQUE CONTROL PRINCIPLE

The main blocs constituting the conventional DTC scheme are represented in Figure 1. The values of the stator flux and electromagnetic torque are estimated from the stator currents and voltages. Both flux and torque are controlled directly and independently by the selection of optimal switching states of the inverter.

Indeed, the end of the stator flux vector moves on a line with the direction given by the voltage vector V_s. If the interval is sufficiently small, the average voltage V_s is then constant and we obtain [7]:

$$\Delta\overline{\varphi_s} \approx \overline{V_s} \cdot T_e \tag{6}$$

By adequately selecting voltage vectors available at the output of the inverter, on successive time intervals of time T_e, it is possible to drive the end of the stator flux to a desired path. It is therefore possible to operate with a constant φ_s by driving the end of stator flux vector to an almost circular path.

The principle of the conventional DTC is to control directly the electromagnetic torque while maintaining constant stator flux amplitude. In addition, as indicated in equation (7) which links the stator and rotor fluxes, while the stator flux module is kept constant in the steady state, then the rotor flux amplitude remains constant and its position in relation to the stator flux does not change. The command value of the torque will be directly controlled by the angle between both stator and rotor fluxes vectors as shown by equation (8).

$$\frac{d\varphi_r}{dt} + \left(\frac{1}{\sigma T_r} - j\omega_m\right)\varphi_r = \frac{M}{\sigma L_s T_r}\varphi_s \tag{7}$$

$$C_{em} = p\frac{M}{\sigma L_s L_r}\varphi_s \cdot \varphi_r \cdot \sin(\theta_{sr}) \tag{8}$$

Following an instantaneous increase in the torque command, the action of the direct torque control is to advance the position of the stator flux vector while maintaining its amplitude constant. This will increase the angle θ_{sr} between the two flux vectors and thus instantly increases the value of the electromagnetic torque. The rotor flux will react by returning to a position θ_{sr1} corresponding to the new value of the torque command and the electromagnetic torque reaches the torque command.

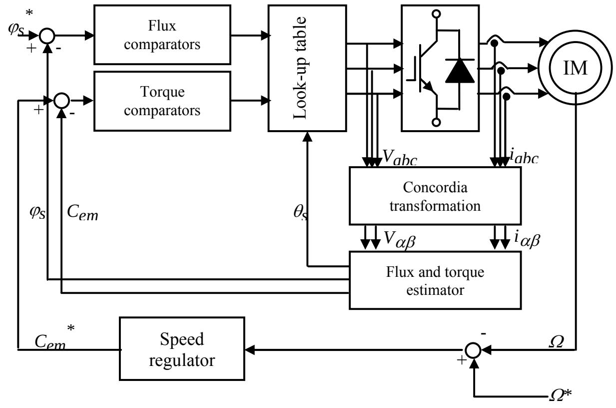

Fig. 1. Conventional direct torque control scheme.

The table 1 shows the look-up table proposed by Takahashi in terms of the flux hysteresis comparator output, the torque hysteresis comparator output and the position of stator flux vector [3].

TABLE 1
TAKAHASHI LOOK-UP TABLE

Zone of φ_s		**1**	**2**	**3**	**4**	**5**	**6**
$\varepsilon_{\varphi s}$	ε_{Cem}						
1	**1**	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	**1**	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

Using the look-up table, we can determine the choice of voltage vectors $V_{i-1}, V_{i+1}, V_{i-2}$ or V_{i+2} corresponding to a zone (i), and this for a two levels hysteresis comparator for the stator flux and a three levels one for the torque.

The stator flux amplitude can be maintained constant only if the direction of the reference voltage vector chosen is perpendicular to the direction of stator flux vector in each period T_e. This is not achievable using the conventional DTC scheme because it has only eight voltage vectors at the output of the inverter allowing the end of flux vectors remain in a band around the reference value. This will result in significant changes in the position of the flux and the value of the electromagnetic torque causing, as a result, high ripples in the torque.

To overcome this problem, we propose the use of the space vector modulation to generate the voltage vector whose position is chosen with the help of a special look-up table and its amplitude calculated through a fuzzy logic estimator so to drive the stator flux vector and the electromagnetic torque to their reference values in an optimal way.

IV. DIRECT TORQUE FUZZY CONTROL PRINCIPLE

The direct torque fuzzy control scheme (DTFC) proposed in [5] employs the space vector modulation. The DTFC scheme is given in Figure 2. Flux and torque errors are used as input to the fuzzy logic estimator of the amplitude of the voltage reference vector V_s and to the hysteresis comparators which deliver the level of errors used by the look-up table of the voltage vector angle.

Unlike the conventional DTC scheme where the voltage vector applied has a constant amplitude whatever the position of the torque outside his hysteresis band; the DTFC scheme allows the calculation of the optimum voltage to be applied to the machine according to the position of torque and stator flux relative to their required values, thus providing a fast and accurate control of the electromagnetic torque. The voltage vector is then synthesized using space vector modulation. The SVM technique generates the inverter switching states.

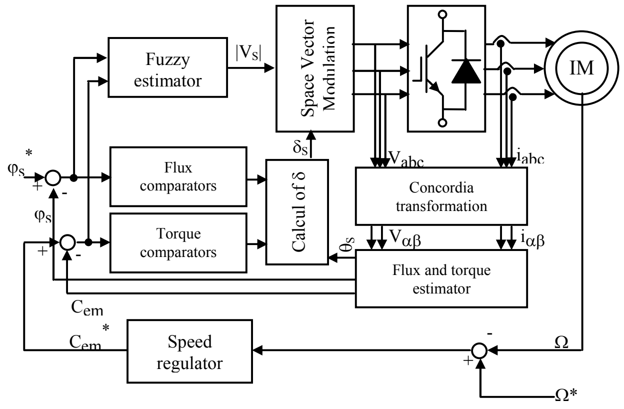

Fig. 2. Direct torque fuzzy control scheme.

A. Selection of the voltage vector position

The position of the voltage vector V_s relative to the stator flux vector must be chosen so as to maintain the stator flux and electromagnetic torque in an optimal error band around their respective reference values.

Indeed, the reference voltage position is obtained by adding an angle to the position of the stator flux. This angle is selected based on the values of hysteresis comparators output. Let $\delta_s = \delta + \theta_s$.

TABLE 2
VOLTAGE VECTOR ANGLE LOOK-UP TABLE

ε_{φ_s}	-1			0			1		
ε_{C_e}	**-1**	**0**	**1**	**-1**	**0**	**1**	**-1**	**0**	**1**
δ	$-\frac{2\pi}{3}$	$+\pi$	$+\frac{2\pi}{3}$	$-\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$-\frac{\pi}{3}$	0	$\frac{\pi}{3}$

It should be noted that the torque and flux hysteresis comparators are both three levels comparators [5].

B. Selection of the voltage vector amplitude

The voltage vector amplitude must be chosen so as to reduce the flux and torque errors. A fuzzy logic estimator is designed to generate appropriate voltage vector amplitude. The bloc diagram of the proposed estimator is given in Fig. 3.

The torque and flux errors signals ε_{C_e} and ε_{φ_s} are multiplied by respective gain factors $G\varepsilon_{C_e}$ and $G\varepsilon_{\varphi_s}$ in order to obtain the fuzzification bloc input signals ε_{nC_e} and $\varepsilon_{n\varphi_s}$. For a successful design of the fuzzy logic estimator, appropriate tuning of these gains is necessary. The fuzzification bloc converts the crisp variables ($\varepsilon_{nC_e}, \varepsilon_{n\varphi_s}$) into fuzzy variables ($\tilde{e}_{C_e}, \tilde{e}_{\varphi_s}$) using the triangular membership functions.

The input membership functions are used to transfer crisp inputs into fuzzy sets. The inference engine bloc, based on the input fuzzy variables ($\tilde{e}_{C_e}, \tilde{e}_{\varphi_s}$), uses forty nine (49) '*if then*' rules, where the *and* method corresponds to the minimum fuzzy inputs, in order to obtain the final output fuzzy sets as shown in table 3. These rules have been set so as to take maximal voltage vector amplitude when the torque is outside its error band, otherwise zero amplitude is assigned. The defuzification bloc uses the gravity centre technique to transform the fuzzy set to a crisp output. The voltage vector amplitude is then obtained by multiplying the crisp output value (*du*) by an appropriate weight. The output weight is chosen so that the maximum voltage vector amplitude should not exceed the maximum amplitude of a voltage vector generated by a two level PWM inverter [8].

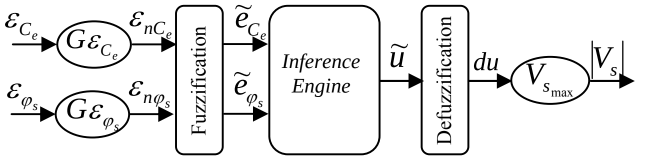

Fig. 3. Proposed fuzzy estimator for voltage vector amplitude.

TABLE 3
RULE BASE FOR VOLTAGE AMPLITUDE ESTIMATOR

$\tilde{e}_{Ce}$ / $\tilde{e}_{\varphi}$	**NH**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PH**
NH	PH	PM	PS	PS	PS	PM	PH
NM	PH	PM	PS	PS	PS	PM	PH
NS	PH	PM	PS	ZE	PS	PM	PH
ZE	PH	PM	PS	ZE	PS	PM	PH
PS	PH	PM	PS	ZE	PS	PM	PH
PM	PH	PM	PS	PS	PS	PM	PH
PH	PH	PM	PS	PS	PS	PM	PH

NH: negative high, **NM**: negative medium, **NS**: negative small, **ZE**: zero, **PS**: positive small, **PM**: positive medium, **PH**: positive high.

The I/O mapping of the fuzzy logic vector voltage amplitude estimator is given in figure 4.

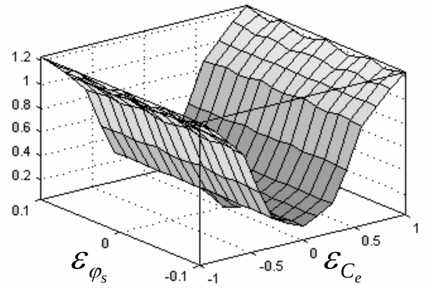

Fig. 4. Proposed fuzzy logic estimator I/O Map.

V. SIMULATION RESULTS

The simulation of the conventional DTC scheme and the DTFC scheme is achieved using MATLAB/ SIMULINK tools. Figure 5 shows the simulation results of the conventional DTC scheme.

The induction motor is started at full load (10 N/m). The stator current is characterized by a high distortion. We also observed high peak-to-peak electromagnetic torque ripple of 4.2 N/m around its reference. The stator flux reached immediately its reference value of 1.2 Wb with a slight overshoot of 0.08 Wb peak-to-peak value and the trajectory of the stator flux takes an almost circular shape with a slight deviation at the border change from the zone of the stator flux vector.

Figure 6 shows the simulation results of the DTFC scheme. The inverter operates with a switching frequency of 10 KHz. We notice a net improvement in the stator current form which seems sinusoidal with no ripples in the steady state. Electromagnetic torque shows a peak-to-peak ripple of 0.21 N/m around his reference.

There is a considerable reduction in the degree of torque ripple. The peak-to-peak ripple of stator flux is reduced to 0.01 Wb. Finally, we can observe a perfectly circular trajectory in the stator flux, which is reflected in a constant amplitude operation of the stator flux.

We used the same speed regulator for the conventional DTC and DTFC schemes. Indeed, a variable gain PI controller (VGPI) is used to generate the torque command depending on the error between the measured speed and the reference speed (1000 rpm).

VI. CONCLUSION

In this paper, we used a new strategy to control the voltage source inverter with the DTC concept, which is a combination of space vector modulation and hysteresis comparators. We proposed a fuzzy logic estimator for the determination of the optimal voltage vector amplitude to be applied to the machine.

The DTFC scheme is proposed to reduce the ripples that can be seen in electromagnetic torque and stator flux and also improve the form of the stator current. The DTFC scheme achieved on the basis of the conventional DTC scheme has also shown through the different simulations its effectiveness, and superiority to the conventional DTC scheme, particularly regarding the objectives aimed by this study.

VII. APPENDIX

INDUCTION MACHINE PARAMETERS

Number of pairs of poles	2
Rated power	2 hp
Rated frequency	50 Hz
Rated speed	1420 rpm
Rated voltage	220/380 V
Rated current	6.4/3.7 A
Stator resistance	4.85 Ω
Rotor resistance	3.805 Ω
Stator inductance	274 mH
Rotor inductance	274 mH
Mutual inductance	258 mH
Moment of inertia	0.031 kg.m²
Viscous friction coefficient	0.00114 kg.m²/s

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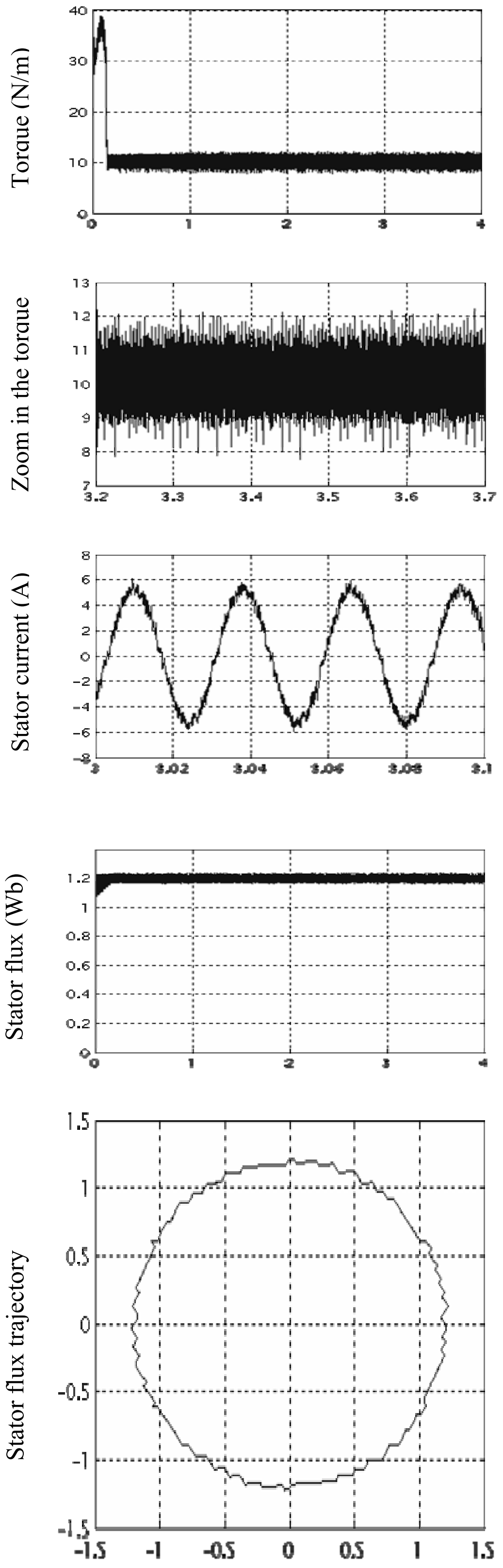

Fig. 5. Simulation results of the conventional DTC scheme.

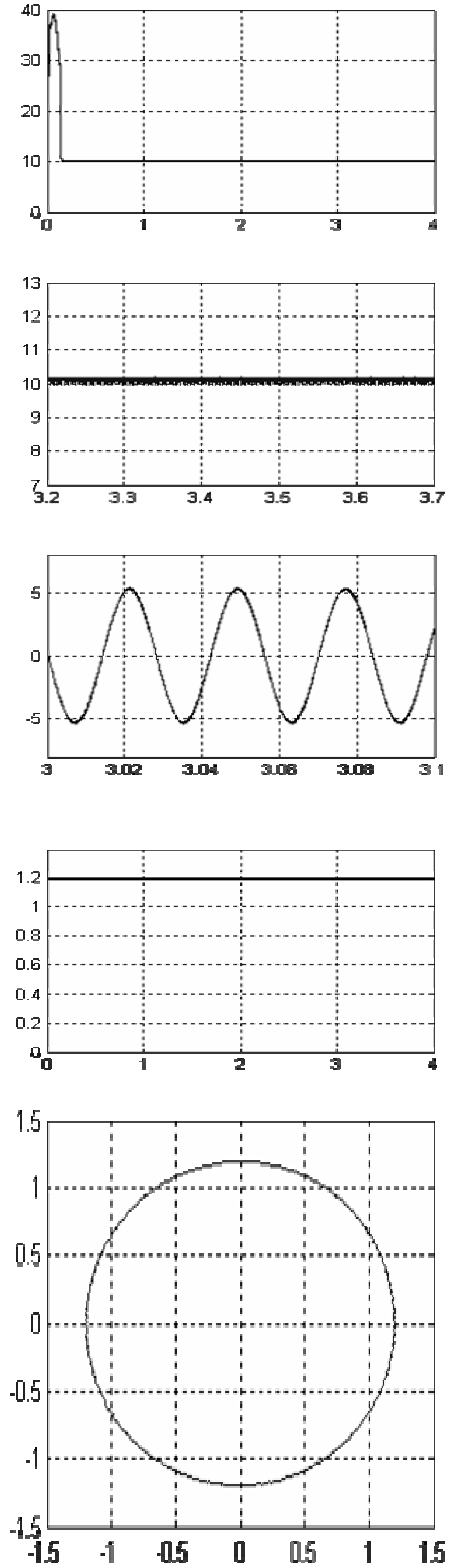

Fig. 6. Simulation results of the DTFC scheme.