

# Direct Torque Control of Induction Motor Drive Using Pi-Fuzzy Logic Controller

Venkatesh.G, Bagavathy.S

Department of ECE, SKCE, Coimbatore, India

Department of ECE, SKCE, Coimbatore, India

**ABSTRACT**— Direct Torque Control (DTC) of an induction motor fed by a voltage source inverter is a simple scheme that does not need long computation time and can be implanted without mechanical speed sensors and is insensitive to parameter variations. In principle, the motor terminal voltages and currents are sampled and used to estimate the motor flux and torque. Based on estimates of the flux position and the instantaneous errors in torque and stator flux magnitude, a voltage vector is selected to restrict the torque and the flux errors within their respective torque and flux hysteresis bands.

In the conventional DTC, the selected voltage vector is applied for the whole switching period regardless of the magnitude of the torque error. This can result in high torque ripple. This paper aims in comparison of different techniques followed for torque ripple minimization in induction motor drive.

**KEYWORDS**— Direct Torque Control (DTC), Induction Motor Control, Torque Ripple Reduction.

## I. INTRODUCTION

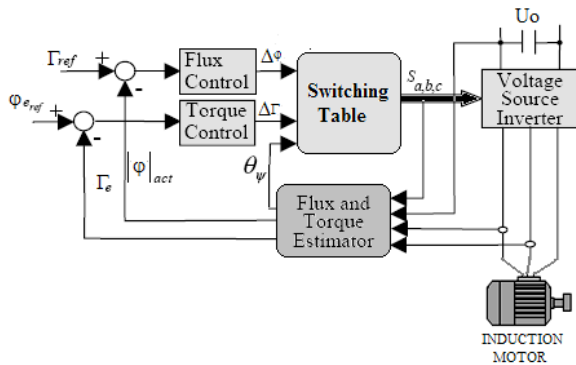
The direct torque control (DTC) is one of the actively control scheme. It is based on the decoupled control of flux and torque. DTC provides a very quick and precise torque response without the complex field-orientation block and the inner current regulation loop [1]–[3]. There have been some DTC-based strategies, e.g., voltage-vector selection using switching table [1], direct self-control [2], and space-vector modulation [3]. Among them, the voltage vector selection strategy using a switching table is widely researched and commercialized [4] because it is very simple in concept and easy to be implemented without complicated over modulation technique, which is unavoidable in space vector pulse width modulation

(PWM) [5]. However, the DTC strategy using a switching table (hereafter simply referred to as DTC) has some drawbacks. switching frequency varies according to the motor speed and the hysteresis bands of torque and flux[5].

Large torque ripple is generated which has to be minimized [5]. Although the inverter switching frequency can be increased by mixing high frequency dither signals with the error signals of torque and flux, respectively, the inverter switching frequency is not constant for small error bands [6] and the difficulty of designing inverter output filter becomes difficult. For the DTC based drives, the torque ripple is significantly for not invoking the zero inverter switching states; especially at motor start-up [7] The problem of reducing the torque ripple in conventional DTC has studied by many researchers, which have proposed solutions for it .One approach is to increase the number of voltage vectors applied in a sampling period, using some sorts of pulse width modulation (PWM). Among the possible choices, a simpler one is to use two voltage vectors: a nonzero one, applied for a fraction of the sampling period, and the null vector for the rest. The duty ratio (the ratio of active vector duration to the whole period) must be calculated each sample period, and by varying it between its extreme values. it is possible to apply more voltage levels to the motor, according to the desired torque variation. In [8], an analytical online algorithm calculates the optimum duty ratio each sampling period, by using torque ripple minimization condition, it is based on ripple equations.

However, this algorithm requires high computational effort and additional motor parameters to be known. In [9] the duty ratio value is provided by a new fuzzy logic module, whose inputs are the stator flux position, the electromagnetic torque and an input defining the motor operating point, given by the speed and the torque values. This algorithm involves expert knowledge and needs the rotor speed. To overcome this

problem, this paper proposes a solution, which consists in the modulation of the nonzero voltage vector duration over a sampling period, according to the instant values of the torque and stator flux errors.



DTC technique

II. DIRECT TORQUE CONTROL

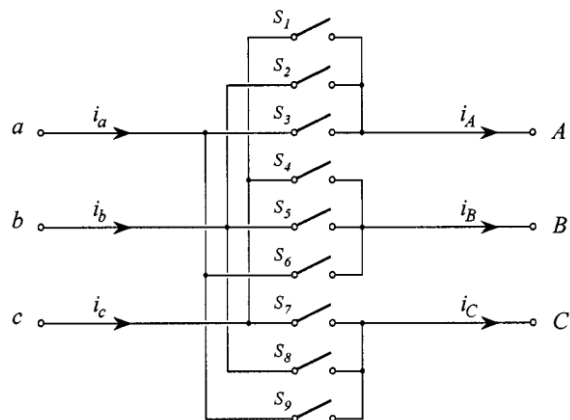
The DTC scheme is very simple in function; in its basic configuration it consists of hysteresis controllers, torque and flux estimator and a switching table. The basic concept of DTC is to control directly both the stator flux linkage (or rotor flux linkage, or magnetizing flux linkage) and electromagnetic torque of machine simultaneously by the selection of optimum inverter switching modes. The use of a switching table for voltage vector selection provides fast torque response, low inverter switching frequency and low harmonic losses without the complex field orientation by restricting the flux and torque errors within respective flux and torque hysteresis bands with the optimum selection being made. The DTC controller consists of two hysteresis comparator (flux and torque) to select the switching voltage vector in order to maintain flux and torque between upper and lower limit. The DTC scheme of induction motor drive is explained in detail.[10]

A. Matrix Converters in Direct Torque Control of Induction Machines

A new control method for matrix converters is proposed which allows, under the constraint of unity input power factor, the generation of the voltage vectors required to implement the DTC of induction machines. The appropriate switching configuration of the matrix converter is directly selected, at each sampling period, using an opportune switching table. The table is entered by the outputs of three hysteresis controllers applied to the errors of stator flux, electromagnetic torque, and input power factor, respectively. Using this control method, it is possible to combine the advantages of matrix converters with the advantages of DTC schemes.[11].

The good performance of the proposed scheme has been tested using a realistic numerical simulation of the whole drive. The steady-state and the transient behavior have been investigated. In both cases, the results

obtained emphasize the effectiveness of the proposed drive system. Experimental tests proving the feasibility of such control scheme have been carried out. Some considerations in order to improve the drive performance are also presented.



In principle, the DTC is a hysteresis stator flux and torque control that directly selects one of the six nonzero and two zero voltage vectors generated by a VSI, in order to maintain the estimated stator flux and torque within the hysteresis bands.

In particular, the stator flux is controlled by a two-level hysteresis comparator, whereas the torque by a three-level hysteresis comparator, as shown in Figs. 5 and 6, respectively. On the basis of the hysteresis comparator outputs and the stator flux sector number, the most opportune VSI voltage vector is selected at each sampling period, according to the switching table.

		①	②	③	④	⑤	⑥
$c_\phi = -1$	$c_T = -1$	$V_2$	$V_3$	$V_4$	$V_5$	$V_6$	$V_1$
	$c_T = 0$	$V_7$	$V_0$	$V_7$	$V_0$	$V_7$	$V_0$
	$c_T = +1$	$V_6$	$V_1$	$V_2$	$V_3$	$V_4$	$V_5$
$c_\phi = +1$	$c_T = -1$	$V_3$	$V_4$	$V_5$	$V_6$	$V_1$	$V_2$
	$c_T = 0$	$V_0$	$V_7$	$V_0$	$V_7$	$V_0$	$V_7$
	$c_T = +1$	$V_5$	$V_6$	$V_1$	$V_2$	$V_3$	$V_4$

Basic DTC Switching Table

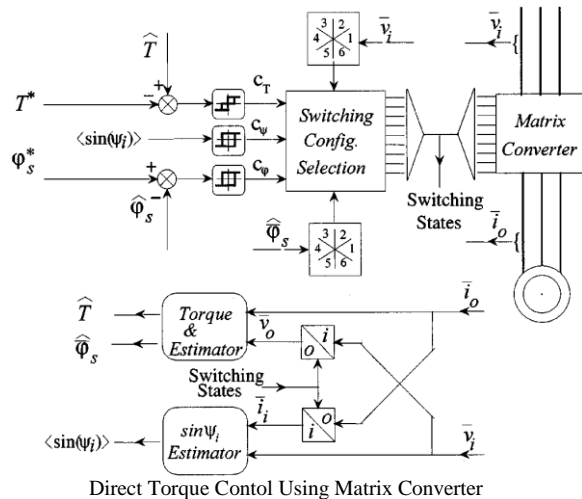
Switching Configuration	A	B	C	$V_o$	$\alpha_o$	$i_i$	$\beta_i$
+1	a	b	b	$2/3 v_{ab}$	0	$2/\sqrt{3} i_A$	$-\pi/6$
-1	b	a	a	$-2/3 v_{ab}$	0	$-2/\sqrt{3} i_A$	$-\pi/6$
+2	b	c	c	$2/3 v_{bc}$	0	$2/\sqrt{3} i_A$	$\pi/2$
-2	c	b	b	$-2/3 v_{bc}$	0	$-2/\sqrt{3} i_A$	$\pi/2$
+3	c	a	a	$2/3 v_{ca}$	0	$2/\sqrt{3} i_A$	$7\pi/6$
-3	a	c	c	$-2/3 v_{ca}$	0	$-2/\sqrt{3} i_A$	$7\pi/6$
+4	b	a	b	$2/3 v_{ab}$	$2\pi/3$	$2/\sqrt{3} i_B$	$-\pi/6$
-4	a	b	a	$-2/3 v_{ab}$	$2\pi/3$	$-2/\sqrt{3} i_B$	$-\pi/6$
+5	c	b	c	$2/3 v_{bc}$	$2\pi/3$	$2/\sqrt{3} i_B$	$\pi/2$
-5	b	c	b	$-2/3 v_{bc}$	$2\pi/3$	$-2/\sqrt{3} i_B$	$\pi/2$
+6	a	c	a	$2/3 v_{ca}$	$2\pi/3$	$2/\sqrt{3} i_B$	$7\pi/6$
-6	c	a	c	$-2/3 v_{ca}$	$2\pi/3$	$-2/\sqrt{3} i_B$	$7\pi/6$
+7	b	b	a	$2/3 v_{ab}$	$4\pi/3$	$2/\sqrt{3} i_C$	$-\pi/6$
-7	a	a	b	$-2/3 v_{ab}$	$4\pi/3$	$-2/\sqrt{3} i_C$	$-\pi/6$
+8	c	c	b	$2/3 v_{bc}$	$4\pi/3$	$2/\sqrt{3} i_C$	$\pi/2$
-8	b	b	c	$-2/3 v_{bc}$	$4\pi/3$	$-2/\sqrt{3} i_C$	$\pi/2$
+9	a	a	c	$2/3 v_{ca}$	$4\pi/3$	$2/\sqrt{3} i_C$	$7\pi/6$
-9	c	c	a	$-2/3 v_{ca}$	$4\pi/3$	$-2/\sqrt{3} i_C$	$7\pi/6$
0 <sub>a</sub>	a	a	a	0	-	0	-
0 <sub>b</sub>	b	b	b	0	-	0	-
0 <sub>c</sub>	c	c	c	0	-	0	-

the matrix converter generates a higher number of output voltage vectors with respect to VSI. This feature can be utilized to keep under control a further variable in addition to stator flux and torque.[12] In the proposed control method, the average value of the sine of the displacement angle between the input line-to-neutral voltage vector and the corresponding input line current vector has been chosen as a third variable.

In principle, the proposed control technique of the matrix converter selects, at each sampling period, the proper switching configuration, which allows the compensation of instantaneous errors in flux magnitude, and torque, under the constraint of unity input power factor.[13] This last requirement of the input side of the matrix converter is intrinsically satisfied if the average value of is maintained close to zero.

	1		2		3		4		5		6	
$c_\psi$	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1
$V_1$	-3	1	2	-3	-1	2	3	-1	-2	3	1	-2
$V_2$	9	-7	-8	9	7	-8	-9	7	8	-9	-7	8
$V_3$	-6	4	5	-6	-4	5	6	-4	-5	6	4	-5
$V_4$	3	-1	-2	3	1	-2	-3	1	2	-3	-1	2
$V_5$	-9	7	8	-9	-7	8	9	-7	-8	9	7	-8
$V_6$	6	-4	-5	6	4	-5	-6	4	5	-6	-4	5

Matrix Converter Switching Table



**B. DTC USING SPACE VECTOR MODULATION**

It is considered as an alternative to field oriented control technique. The Direct Torque Control scheme is characterized by the absence of PI regulators, coordinate transformations, current regulators and pulse width modulated signal generators. Direct Torque Control allows a good torque control in steady state and transient operating conditions. The direct torque control technique based on space vector modulation and switching table has been developed. The flux linkage and torque errors are restricted within its respective hysteresis bands. It can be proved that the flux hysteresis band affects the stator-current distortion in terms of low order harmonics and the torque hysteresis band affects the switching frequency.[14] The DTC requires the flux and torque estimations, which can be performed as proposed in this model, by means of two different phase currents and the state of the inverter. The flux and torque estimations can be performed by means of other estimators using other magnitudes such as two stator currents and the mechanical speed, or two stator currents again and the shaft position [15].

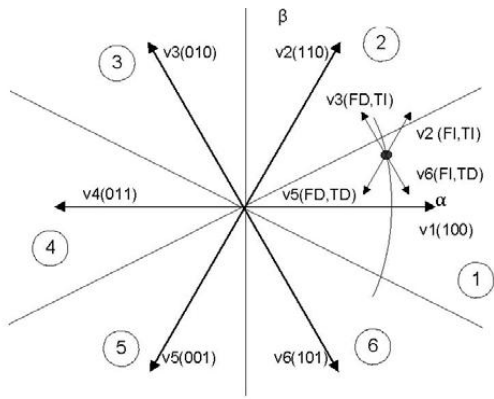
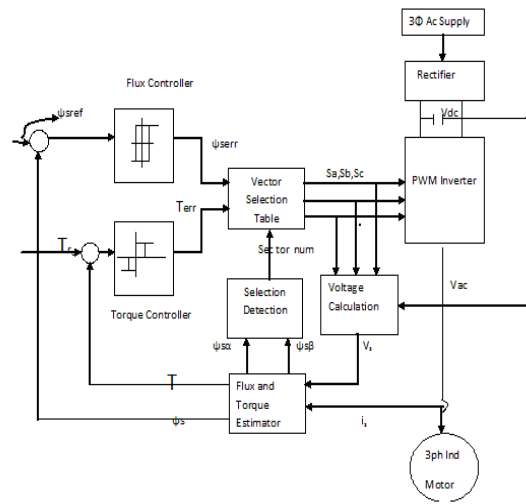


Fig.1 The stator flux switching sector.

DTC algorithm selects the inverter voltage vector from the Table 1. The outputs of the switching table are the settings for the switching devices of the inverter. Fig.2 shows the relation of inverter voltage vector and stator flux switching sectors. Six active switching vectors V1, V2, V3, V4, V5, V6 and two zero switching vectors V0 and V7 determine the switching sequence of the inverter. Depending on inverter switching pulses, PWM is achieved and hence stator voltages and currents are controlled [13]. Therefore to obtain a good dynamic performance, an appropriate inverter voltage vectors  $V_i$  ( $i=1$  to 6) has to be selected.



The main features of DTC can be summarized as follows. DTC operates with closed torque and flux loops but without current controllers. DTC needs stator flux and torque estimation and, therefore, is not sensitive to rotor parameters. DTC is inherently a motion-sensor less control method. DTC has a simple and robust control structure.

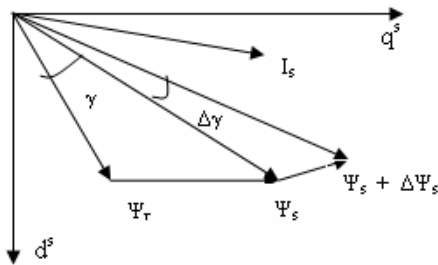


Fig. 2 Stator and flux vector

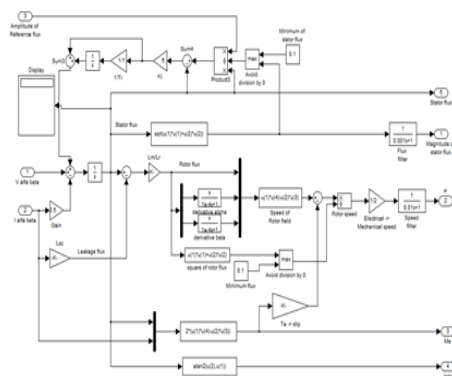
- Input Parameters to the Simulation
- P=No.of Pair poles=2
- Rs=0.5;
- Rr=0.25;
- Ls=0.0415;
- Lr=0.0412;
- Lm=0.0403;
- Lsc=0.0018;
- [Power= 4000; V=400; f=50]

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### Measurement of stator and rotor flux:



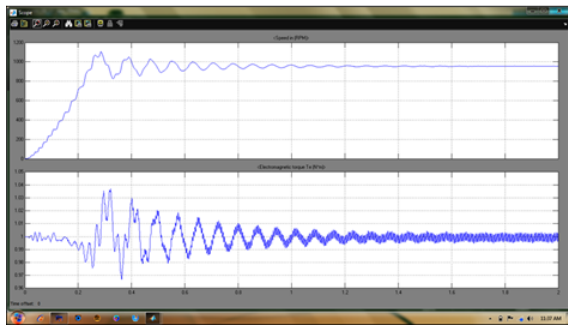
### III. DTC USING FUZZY LOGIC

To obtain improved performance of DTC drive during changes in the reference torque, it is possible to use a fuzzy-logic-based switching vector selection process. For this purpose a Mamdani-type fuzzy logic system will be used. The different output voltage states (active and zero states) are selected by using three inputs: flux  $e_\psi$  and torque  $e_\tau$  errors and also the position of the stator flux linkage space vector  $u_s$ . For this purpose it is assumed that the stator flux linkage space vector can be located in any of twelve sectors, each spanning over a  $60^\circ$  wide region. For every sector there are 15 rules. The Stator flux error ( $e_\psi$ ) has three fuzzy sets: stator error can be positive P, zero ZE, and negative N. For the torque error, there are five fuzzy sets: the torque error ( $e_\tau$ ) can be positive large PL, positive small PS, zero ZE, negative small NS and negative large NL (Figs. 5,6,7,8). Since there are 12 sectors, for each sector 15 rules, the total

number of rules is 180.mode approach, the engine will turn on only once, i.e., when the HEV switches to either non hybrid or hybrid mode. The second and third cases are for rule-based and optimization-based blended controllers, respectively.

IV. RESULTS

Torque ripple reduction with PI –FUZZY controller



The fuzzy logic has been proved powerful and able to resolve many problems. A fuzzy controller seems to be a reasonable choice to evaluate the amplitude of torque hysteresis band according to the torque ripple level. In this paper, the amplitude of torque hysteresis band is not prefixed but it is determinate by a fuzzy controller. Based on the analysis given in section (B),two inputs are chosen, speed error variation and stator current variation. The fuzzy controller design is based on intuition and simulation. For different values of motor speed and current, the values reducing torque and flux ripple were found. These values composed a training set which is used to extract the table rule. The shapes of membership functions are refined trough simulation and testing.

MEMBERSHIP FUNCTIONS

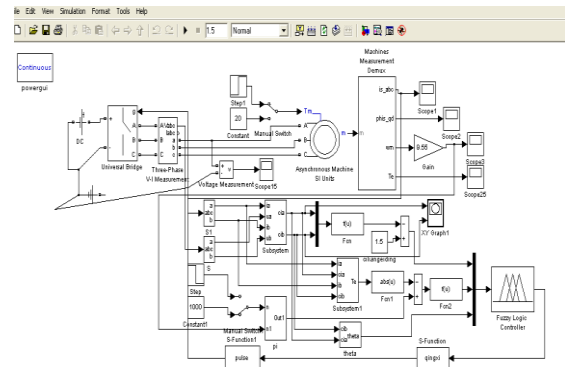
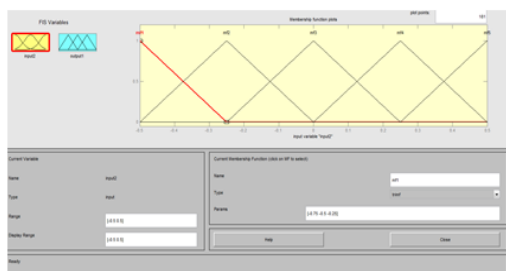


Fig.3. simulation using FLC

Many intelligent control techniques are employed for control of induction motor drives. The SPWM technique produce reference which tends to be trapezoidal in nature.to overcome this SVPWM technique was employed to reduce the torque ripple. FLC improved the system performance dramatically.

V. CONCLUSIONS

In this paper, survey on DTC control techniques of SVPWM and FLC was studied. This controller determinates the desired amplitude torque hysteresis band. It is shown that the proposed scheme results in improved stator flux and torque responses under steady state condition. The main advantage is the improvement of torque and flux ripple characteristics at low speed region; this provides an opportunity for motor operation under minimum switching loss and noise. This controller determinates the desired amplitude of torque hysteresis band. It is shown that the proposed scheme results in improved stator flux and torque responses under steady state condition.

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