Torque Ripple Minimization in Direct Torque Control of Induction Motor using Fuzzy Technique

Pandian . A[1] and Dhanasekaran .R[2]

[1.] Associate Professor, Department of Electrical and Electronics Engineering, Angel College of Engineering and Technology, Tirupur -641665, Tamil Nadu, India. pands_2@yahoo.com

[2.] Research Director and Professor, Syed Ammal Engineering College, Ramanathapuram -623502, Tamil Nadu, India

Abstract: In this paper presents the new approach of DTC by Fuzzy technique to reduce the torque ripples. It consists of Induction Motors and a Three-Level IGBT inverter with the fuzzy based PI controller. Thus the fuzzy control should need the efficient possible rules. Fuzzy based controllers develop a control signal which yields on the firing of the rule base, these rules are fired which is random in nature and the rule for speed regulation. This becomes an integrated method of approach for the control purposes and achieves the reduction of torque ripple. The simulation results presented in this paper show the effectiveness of the method developed and has got faster response time or settling times.

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Keywords: Direct Torque Control (DTC), Fuzzy Controller, Induction Motor, Space Vector Modulation, Stator Flux, Three-Level Inverter.

1. Introduction

Three Phase Induction Motor is mostly used as the prime mover in industries, it's due to the induction motor has simple construction, sturdy, easy maintenance and relatively low price, therefore the induction motor has start shifting the use of other prime mover in industries[1]. The induction motor has some non linear parameters, especially rotor resistance, which has a wide variation in value for the difference of operation condition. The load change at the induction motor it will create change in motor speed, so that to keep motor speed constant, as it needs some controller which could adapt the change of motors load. Accurate control of electrical machines requires an independent control of magnetic flux and torque.

Induction motor drives controlled by stator and rotor currents, so due to this fact in the later eighties a new control method Direct Torque Control (DTC) is invented [3]. It's characterized by its simple application and a good fast dynamic response. We can remove the following common disadvantages of DTC likewise high torque ripple and slow transient response to the step changes in torque during start-up, by applying modern intelligent techniques like fuzzy logic. Due to that reason, the application of fuzzy logic control attracts the attention of many researchers from all over the world.

Fuzzy control is a way for controlling a system without the need of knowing the plant mathematic model. It uses the experience of people's knowledge to form its control rule base.

2. Concept of Direct Torque Control

The basic functional blocks used to implement the DTC scheme are represented in Figure1. The instantaneous values of the stator flux and torque are calculated from stator variable by using a closed loop estimator [2]. Stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configuration. This method is based on maintaining the amplitude and the phase of the stator current constants. An induction machine can be modeled with stator current and flux reference values. The estimated values of the stator flux and torque are compared to their reference values and the switching states are selected according to the switching table selector. The DTC requires the flux and torque estimations, which can be performed as it is proposed, by means of two different phase currents and the state of the inverter. However, flux and torque estimations can be performed using other magnitudes such as two stator currents and the shaft position [4]. The direct torque control method has been derived depending on the basis of the errors between the reference and the estimated values of torque and flux. It is easy to control the inverter states directly for getting the reduced torque and flux errors within the predefined band limits [5]. It controls the torque on the basis of keeping the flux value invariable by choosing voltage space vector.

In a direct torque controlled induction motor drive supplied by a voltage source inverter, it is possible to directly control the stator flux linkage and the electro-magnetic torque by the selection of the optimum stator voltage space vectors in the inverter.

The selection of the most appropriate voltage vector is done in such a way that the flux and torque errors are restricted within the respective flux and torque hysteresis bands, fast torque response is obtained, and the inverter switching frequency is kept at the lowest possible level.

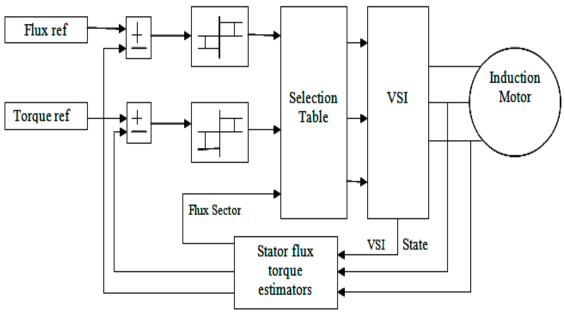

Figure 1.Conventional method of DTC

In the case of rotor flux oriented control of an induction motor, the electromagnetic torque developed by the motor is described by

$$T_e = (3/2)P(L_m / L_r)\psi_r i_{qs} \qquad (1)$$

where the stator q-axis current is the imaginary component of the stator current space vector in the co-ordinate system fixed to the rotor flux space vector.

The torque equation (1) can be written in terms of the amplitude and phase of the stator current space vector with respect to the d-axis of the reference frame as

$$T_e = K\psi_r \left| \underline{i}_s \right| \sin\lambda \qquad (2)$$

Instantaneous change of the torque requires, according to equation (2), change in the amplitude and phase of the stator current space vector, such that the d-axis current component remains the same (so that rotor flux is constant), while the torque is stepped to the new appropriate value by the change in the stator q-axis current component.

An alternative expression for the torque uses the stator flux space vector and stator current space vector. Regardless of the applied method of control, the torque developed by the motor can be written as

$$T_e = \frac{3}{2}P\left|\underline{\psi}_s\right|\left|\underline{i}_s\right|\sin\alpha \qquad (3)$$

where the angle α is the instantaneous value of the angle between the stator current and stator flux space vectors. Figure 2.shows the stator current space vector and stator flux space vector's relative positions.

It can be shown [7] that at certain rotor speeds, if the amplitude of the stator flux is kept constant, an electromagnetic torque can be changed rapidly by altering its instantaneous position so that angle a in equation (3) is rapidly changed. In other words, if such stator voltages are

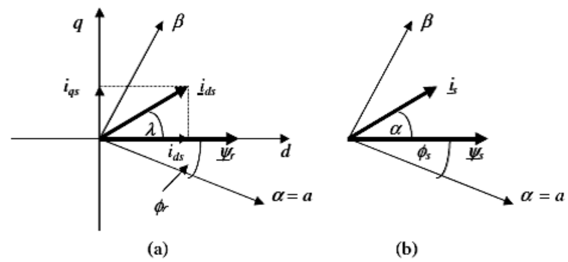

Figure 2.(a) Stator current and rotor flux space vectors in a rotor flux oriented induction machine;
(b) Stator current and stator flux's relative position in an induction machine

imposed on the motor, which keep the stator flux constant (at the set value), but which also quickly rotate the stator flux space vector into the required position (determined by the torque command), then fast torque control is obtained. It follows that if in the DTC drive the developed torque is smaller than the reference, the torque should be increased by using the maximum possible rate of change of the stator flux space vector position f_S.

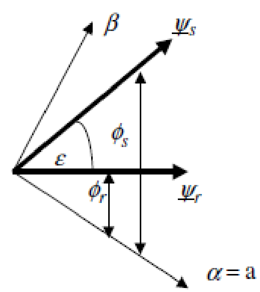

Figure 3 Relative positions of stator flux and rotor flux space vectors

If the stator flux space vector is accelerated in the forward direction, an increase in torque is produced; however, when it is decelerated backwards, a decrease in torque results. The stator flux space vector can be adjusted by using the appropriate stator voltage space vectors, obtainable from the VSI operated in the PWM mode. Thus there is a direct stator flux and torque control achieved by means of the voltage source, hence the name ‘DTC.’ Another form of the torque equation (Figure 2) is the one given in terms of stator and rotor flux:

$$T_e = \frac{3}{2} P \frac{L_m}{\sigma L_s L_r} \left|\underline{\psi}_r\right| \left|\underline{\psi}_s\right| \sin \varepsilon \qquad (4)$$

where ε is the angle between stator flux and rotor flux space vectors.

Rotor flux changes slowly because its rate of change depends on a relatively large rotor time constant; therefore, it can be assumed to be constant in a short period of time. The stator flux amplitude is also kept constant in the DTC control scheme; hence both the vectors in the equation (5.4) have constant amplitudes. Rapid change of torque can be obtained if instan- taneous positions of the stator flux space vector are changed quickly so that « is quickly varied. This is the essence of DTC. The instantaneous change of « can be obtained by switching on the appropriate stator voltage space vector of the VSI.

If stator resistance voltage drop is neglected, the stator voltage equation in the stationary reference frame is

$$\underline{v}_s = d\underline{\psi}_s / dt \qquad (5)$$

Hence the applied stator voltage directly impresses the stator flux. If the voltage abruptly changes, then stator flux will change accordingly to satisfy equation (5). The variation of the stator flux changes during a short period of time when the stator voltage is changed as $\Delta \underline{\Psi}_s = \underline{v}_s \Delta t$

This shows that the stator flux space vector moves in the direction of the applied stator voltage space vector during this period. By selecting the appropriate stator voltage space vectors in subsequent time intervals, it is then possible to change the stator flux in the desired way. Decoupled control of the stator flux and torque is achieved by acting on the radial and tangential components of the stator flux space vector. These two components are directly proportional to the components of the stator voltage space vector in the same directions.

The angle ε between stator and rotor flux space vectors is important in torque production. Assume that the rotor flux space vector is traveling at a given speed, at a certain point in the steady-state operation; this speed is initially equal to the average one of the stator flux space vector. The induction motor is accelerated. Appropriate stator voltage vector is applied to increase torque, and quick rotation of stator flux space vector occurs. However, rotor flux space vector amplitude does not change appreciably, because of the significant rotor time constant. The rotor flux space vector’s speed of rotation is also not changed abruptly; recall that speed of rotation of this vector can be given in terms of rotor flux components and their derivatives; if rotor flux components do not change due to the large time constant, the angular speed of rotor flux space vector does not change either. This will result in an increase of ε that in return increases the motor’s torque. If deceleration is required, an appropriate voltage vector will be applied to reduce the angle « and therefore the decrease the torque developed by the motor. The application of zero voltage vectors will almost stop the rotation of the stator flux space vector. If the angle ε becomes negative, the torque will change signs and a braking process takes place.

3. Three-Level Inverter

A multilevel voltage source inverter is a converter structure that can provide more than two levels of line to ground voltage in the output of each leg of the inverter. Multilevel power conversion technology [6] is a very fast growing area of power electronics with good potential for further development. The most attractive features of this technology are in the medium to high voltage application range, which include motor drives, power distribution, power quality and power conditioning applications. One of the mostly used inverter topology for a three-level inverter is presented in Figure 4.

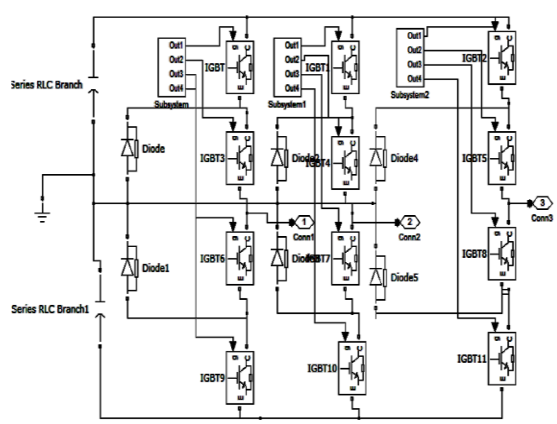

Figure 4. Simu-link Model of Three-Level Inverter

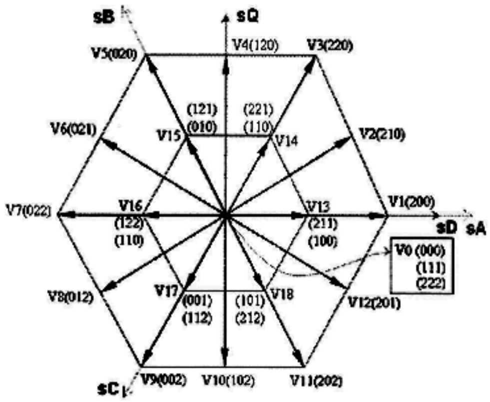

Figure.5. Voltage space vectors of three NPC level Inverter

4. Space Vector Modulation

In Figure 5, the different vectors or inverter states available, in a three-level inverter, are shown in the stator flux locus. As can be seen, there are 4 different kinds of vectors (Table I):

Zero vectors: V0.

Large vectors: VI, V3, V5, V7, V9, V11.

Medium vectors (double): V2, V4, V6, V8, V0, V12.

Small vectors: V13, V14, V15, V16, V17, V18.

Although in a three-level inverter there are 27 possible [6] states (Table I), some of them apply the same voltage vector. There are two possible configurations for each small vector and three for the zero vectors V0. Therefore, 19 different vectors are available in a three level inverter (V0 to V18). The state of the switches for each leg is shown in brackets (2: phase connected to the positive of the DC-link; 1: phase connected to the middle point of the DC-link (Neutral point, NP); 0: phase connected to the negative of the DC-link).

Table 1. Vector Selection Table Modulus

$\Delta\phi_s$	1					0					-1				
ΔC_e	2	1	0	-1	-2	2	1	0	-1	-2	2	1	0	-1	-2
S_1	220	210	200	201	202	120	120	000	102	102	020	121	211	112	002
S_2	020	120	220	210	200	021	021	000	201	201	022	122	221	212	202
S_3	022	021	020	120	220	012	012	000	210	210	002	112	121	211	200
S_4	002	012	022	021	020	102	102	000	120	120	202	212	122	221	220
S_5	202	102	002	012	022	201	201	000	021	021	200	211	112	121	020
S_6	200	201	202	102	002	210	210	000	012	012	220	221	212	122	022

5. Fuzzy Controller Concept

In order to improve the DTC performance an additional use of fuzzy regulator is proposed [3]. The torque fuzzy controller has two inputs (actual error and change in error) and one output [1]. Torque error *E* is divided into seven fuzzy subsets, which are {NB, NM, NS, Z, PS, PM, PB}, Torque error change rate Δ*E* is divided into seven fuzzy subsets {NB, NM, NS, Z, PS, PM, PB} and the output is also divided into seven fuzzy subsets {NB, NM, NS, Z, PS, PM, PB}.

In order to facilitate calculation, triangular and trapezoidal membership functions are used for the fuzz variables.

The fuzzy rule sets are shown in Table.2, in Fig 5 shows the member ship function of input variables and the output variables obtained from the fuzzy controller rule Table.2. The rules were formulated using analysis data obtained from the simulation of the system using different values of torque hysteresis band. According to the rule build the fuzzy control and interface with the DTC, shown in Figure 5.4.

Table 2: Fuzzy Rules

ΔE \ E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

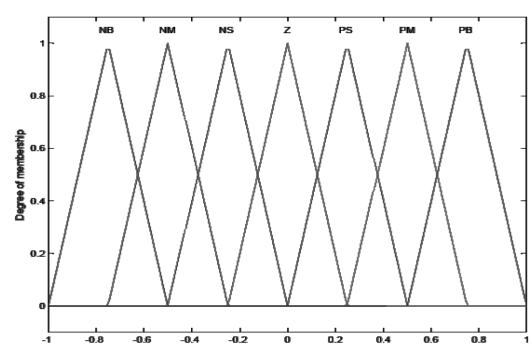

Figure 6: Membership values for Input

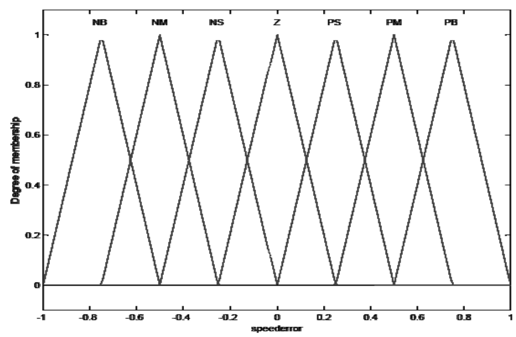

Figure 7: Membership Values for Output

using the basic switching table and the proposed DTFC-SVM. The machine is running at 188 rad/sec. Figure 11 and 12 shows an appreciable reduction of current and torque ripple has been obtained using DTFC-SVM suitable for high rating application in comparison with conventional DTC.

The settling time reaches at 0.04 sec instead of 0.25 in conventional method due to fuzzy controller with time reduction.

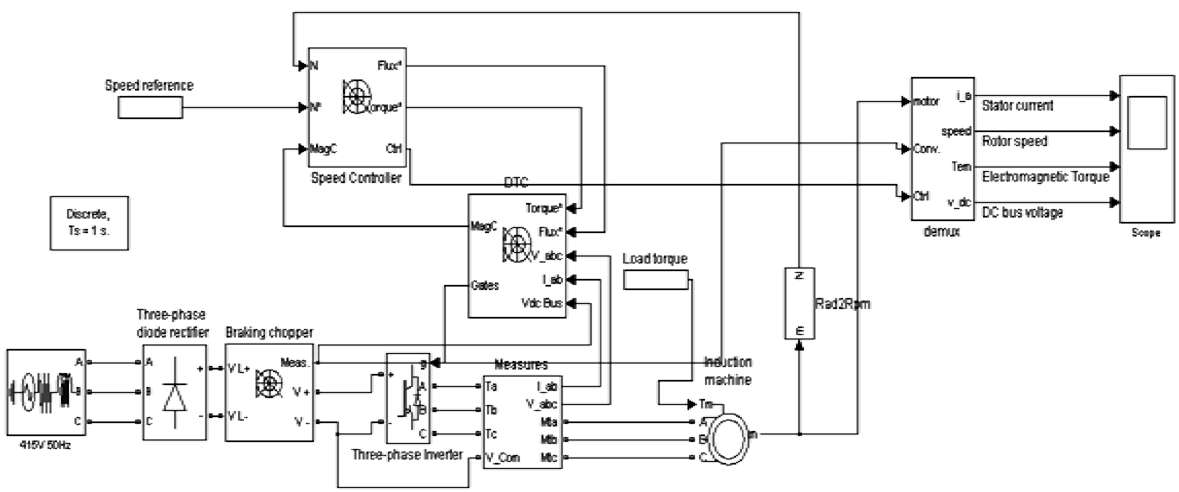

Figure 9: Proposed DTC Model using Matlab

5. Simulation Results

All simulations were performed, by using a model of the Induction Motor in Matlab-Simulink. The parameters of the motors are given in the Appendix-I. All simulations have a sample time for the control loop of 200ms. The simulation carried out is the system response to a torque and stator flux step from zero to the nominal values for both magnitudes.

Figure 8. Shows proposed DTC Model using Matlab. The fuzzy controller and rules are formulated in this block.

A set of 49 fuzzy rules with one output from the fuzzy controller are designed to obtain the optimized output vector.

The Figure.10 shows a comparison between the DTC conventional with three level inverters, and DTFC-SVM with respect to electro-magnetic torque. The comparison of the steady state behavior obtained

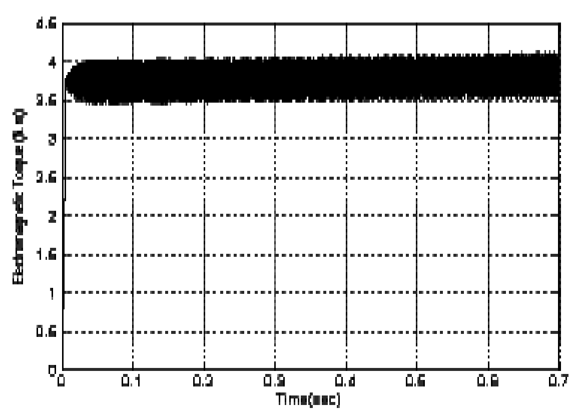

Figure 10: Electromagnetic Torque of Conventional DTC

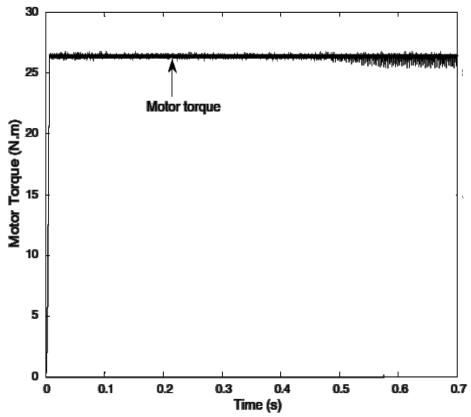

Figure 11: Electromagnetic Torque of Fuzzy Based DTC with SVM

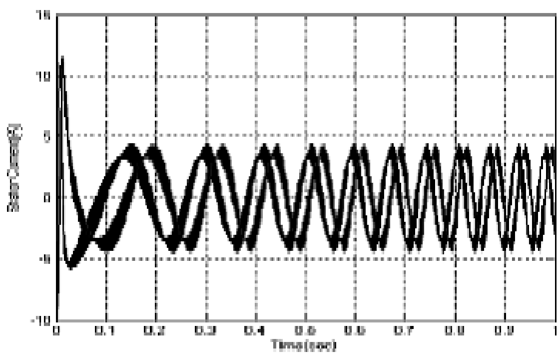

Figure 14: Stator Current of Conventional DTC

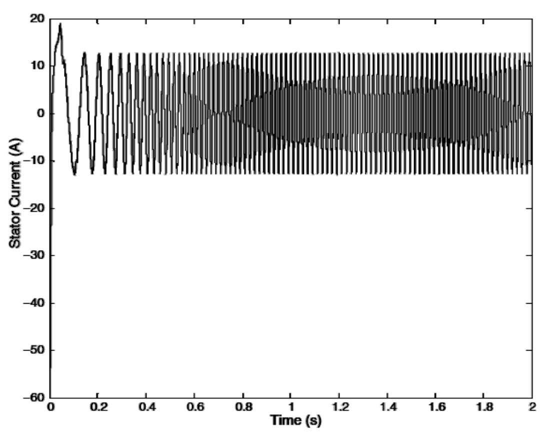

Figure 13: Stator current of Fuzzy based DTC with SVM

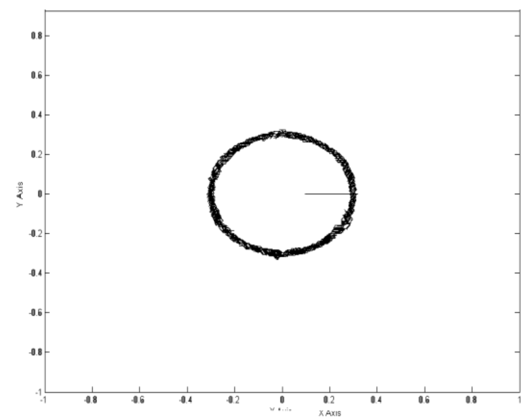

Figure. 14 Flux Trajectory

5. Conclusion

A new fuzzy logic Direct Torque Control scheme based on Space Vector Modulation technique has been presented in this paper. By analyzing the torque waveforms, it shows that torque ripples can be reduced by the fuzzy controller. Its control rules are established based on the prior experience. This approach provides a more accurate selection of the inverter state. Simulations of the novel DTC scheme with fuzzy logic control and space vector modulation show a reduction in torque ripple, stator flux and current distortion in both stator currents and voltages, when compared with conventional DTC with a three-level inverter. The simulation results verify that the proposed fuzzy SVM DTC approach achieved the reduction of torque ripple. This method can be implemented in FPGA to improve the performance in DTC drive.

Appendix-I

Power	*3 hp*
Voltage (L-L)	*380 V*
Stator Resistance	*3.50 ohms*
Rotor resistance	*3.16 ohms*
Stator inductance	*0.3027e-3 H*
Rotor Inductance	*0.3027e-3 H*
Mutual Inductance	*.838 m H*
Number of Poles	*4*
Moment of Inertia	*1.1 kg.m2*
Dc link voltage	*500 V*
Reference Speed	*7.13 rad/sec.*

Proportional Constant *3*
Integrator Constan *0.45*

Corresponding Author:
A.Pandian
Department of Electrical and Electronics Engineering
Angel College of Engineering and Technology
Angel Nagar, P.L.Palayam,
Tirupur – 641665, Tamil Nadu, India
E-Mail: pands_2@yahoo.com

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