SVM-DTC OF AN INDUCTION MOTOR BASED ON VOLTAGE AND STATOR FLUX ANGLE USING FUZZY LOGIC CONTROLLER

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Abstract - *Induction Motors have wide range of applications due to their advantages like rugged construction, low cost and robust performance. In recent years, various aspects are investigated related to controlling induction motor. This paper presents a novel fuzzy space vector modulation direct torque control based on stator voltage amplitude and flux angle.The purpose of SVM-DTC control is to minimize stator current distortion, electromagnetic torque and flux ripples. In this paper, fuzzy logic controllers are proposed to replace the conventional PI torque and flux controllers to achieve desired torque and flux with zero steady state error and also with good tracking and fast response. Fuzzy based flux and torque controllers are designed to optimize voltages in d-q reference frame that applied to SVM. From the output of SVM, motor control signal is developed, hence the speed of Induction Motor is regulated. Simulation is carried out using MATLAB/SIMULINK and the performance of the proposed fuzzy system is analysed. Simulation results showed that a significant improvement in dynamic speed and torque response in steady and transient states and also a considerable reduction in Total Harmonic Distortion (%THD).*

KEY WORDS: *Induction Motor, Space Vector Modulation, Direct Torque Control, Fuzzy logic control,*

1. INTRODUCTION

Over the past years, Direct Torque Control(DTC) of induction motor is widely used control technique in variable frequency drives that produces quick electromagnetic torque [1]. In many industrial applications, DTC has gained great attention due to its advantages like robustness to parameter variations, simple control structure, fast dynamic response, no need of current regulators etc. Space Vector Pulse Width Modulation is drawing more attention for the control of AC machines especially the DTC of IM[2].The DTC scheme can also applicable to low speed ranges also [3].For the robust performance of the DTC-IM drive the adaptive control techniques are introduced[4]. However this control technique has still some disadvantages and they can be mentioned as follows; high current distortion, ripples in torque, variable switching frequency behaviour, difficulty to control torque and flux at very low speed. For digital implementation of DTC, high sampling frequency is needed[5].

On the other hand, artificial intelligent control methods like neural networks and fuzzy logic have been developed by several researchers to incorporate human intuition in the design process[6]-[8]. Fuzzy logic has gained great attention and playing vital role in every area of electromechanical devices control as there is no need of mathematical models like conventional controllers[9].

This study presents a fuzzy logic based SVM-DTC strategy to improve performance of an induction motor. The flux and torque errors act as input to fuzzy logic controllers which produce optimum space vector as output in order to reduce errors. By using this control strategy, advantages of SVM and fuzzy logic control are combined. The response is studied using Matlab/Simulink for the proposed method and the results are analysed.

2. DYNAMIC MODEL OF INDUCTION MOTOR

The induction motor model can be expressed in d-q fixed reference frame by following Eq. (1) to (6):

The stator voltage equation in the d-q reference frame can be described as

$$V_{sdq} = R_s i_{sdq} + \frac{d}{dt}\psi_{sdq} - jW_g\psi_{sdq} \qquad (1)$$

$$0 = R_r i_{rdq} + \frac{d}{dt}\psi_{rdq} - j(W_g - W_r)\psi_{rdq} \qquad (2)$$

Stator and rotor flux linkages in d-q reference frame

$$\psi_{sdq} = l_s i_{sdq} + l_m i_{rdq} \qquad (3)$$

$$\psi_{rdq} = l_r i_{rdq} + l_m i_{sdq} \qquad (4)$$

Electromagnetic torque equation

$$T_e = \frac{3p}{4} L_m(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \qquad (5)$$

$$T_e - T_l = J\frac{d}{dt}W_m + BW_m \qquad (6)$$

where

W_g, W_r, W_m	: Generic reference system, rotor electrical speed, rotor mechanical speed
R_s, R_r	: Stator and rotor resistances
L_s, L_r, L_m	: Stator , rotor and mutual inductances
ψ_{sdq}	: The stator flux in d-q frame
ψ_{rdq}	: Rotor flux in d-q frame
i_{sdq}, i_{rdq}	: Stator and rotor currents in d-q frame
P	: Number of poles
T_e and T_L	: Motor and load torque
B, J	: Friction coefficient and inertia of the system

The equivalent circuits corresponding to these equations in d-q reference frame are illustrated in Fig. 1 and 2

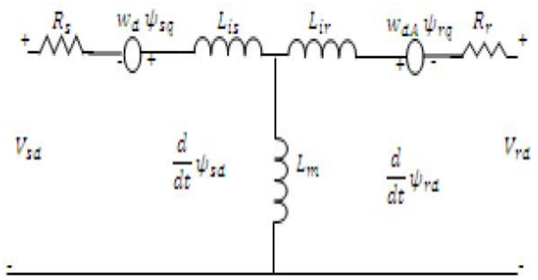

Fig-1: Equivalent circuit of induction motor in d- frame

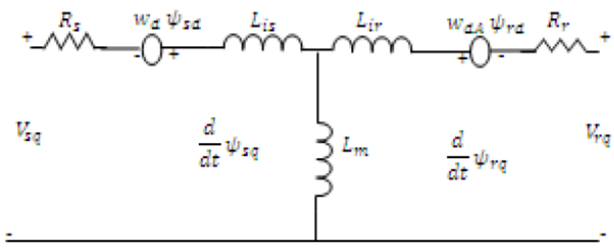

Fig-2: Equivalent circuit of induction motor in q- frame

2.1 Space Vector Modulation (SVM)

Space vector modulation plays a pivotal and practical role in power conversion.Basically it is an algorithm for the control of Pulse Width Modulation(PWM) and used for the production of Alternating Current (AC) waveforms. There are different variations of SVM that result in different quality and computational requirements. One active area of development is in the reduction of Total Harmonic Distortion in output voltages or currents in the windings of the motor load. SV PWM refers to a special method of determining the switching sequence of the upper three power transistors of a three-phase VSI. Stator voltages in αβ reference frame acts as input to SVPWM so that variable voltage and variable frequency of inverter is attained. It is using space vector concept to compute the duty cycle of the switches which is essential implementation of digital control theory of PWM modulators.

Space Vector Modulation technique uses a set of vectors that are defined as instantaneous space-vectors of voltages and currents at the input and output of the converter. The instantaneous three phase voltages can be represented by a space vector in stationary reference frame. These vectors are produced by the different switching states that the converter is able of generating.The eight possible switching states of VSI are indicated as voltage space vectors in a two-level space plane as shown in Fig. 3

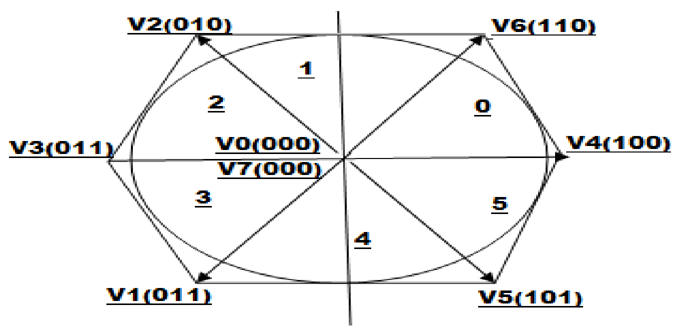

Fig-3 : Space vector diagram

Equations for SVPWM are as follows:

The three phase voltage

$$V_{AO}(t) + V_{BO}(t) + V_{CO}(t) = 0 \quad (7)$$

By using Clark transformation (V_{abc} to $V_{\alpha\beta}$)

$$V_\alpha(t) = \frac{2}{3}\left[V_{AO}(t)\cos(0) + V_{BO}(t)\cos\left(\frac{2\pi}{3}\right) + V_{CO}(t)\cos\left(\frac{4\pi}{3}\right)\right] \quad (8)$$

$$V_\beta(t) = \frac{2}{3}\left[V_{AO}(t)\sin(0) + V_{BO}(t)\sin\left(\frac{2\pi}{3}\right) + V_{CO}(t)\sin\left(\frac{4\pi}{3}\right)\right] \quad (9)$$

$$V(t) = V_\alpha(t) + V_\beta(t) \quad (10)$$

$$V(t) = \frac{2}{3}\left[V_{AO}(t)e^{j0} + V_{BO}(t)e^{j\frac{2\pi}{3}} + V_{CO}(t)e^{j\frac{4\pi}{3}}\right] \quad (11)$$

Where,

$$e^{jx} = \cos(x) + j\sin(x) \quad (12)$$

$$V_{AO}(t) = \frac{2}{3}V_d \quad (13)$$

$$V_{BO}(t) = -\frac{1}{3}V_d \quad (14)$$

$$V_{CO}(t) = -\frac{1}{3}V_d \quad (15)$$

$$V_k = \frac{2}{3}V_d e^{j(k-1)\frac{\pi}{3}} \quad (16)$$

$$V_1 = \frac{2}{3}V_d e^{j\theta}, \text{K} = 1,2,\ldots,6 \quad (17)$$

The main objective of SVM is to approximate the reference voltage by using eight switching pattern(V_0 to V_7). The equations(7 to 17) can be used to develop algorithm for space vector modulation.

3. DTC-SVM STRATEGY

In order to overcome drawbacks in conventional DTC ,Direct flux and torque control with space vector modulation scheme is proposed. In the control structure, PI controllers and space vector modulation(SVM) algorithm is used. The type of DTC-SVM strategy depends on applied flux and torque control algorithm. Amplitude of stator voltage is controlled by PI torque and PI flux controller and then it is realized by space vector modulation approach.

The conventional DTC algorithm is based on instantaneous values from hysteresis flux and torque

controllers and directly intended digital control signals for the inverter.The control algorithm in DTC-SVM approach is based on average values where as the switching signals for the inverter are calculated by space vector modulator which is the main difference between conventional DTC and DTC-SVM control methods. The combined technique of Direct Torque Control(DTC) and Space Vector Modulation(SVM) is shown in Fig. 4.

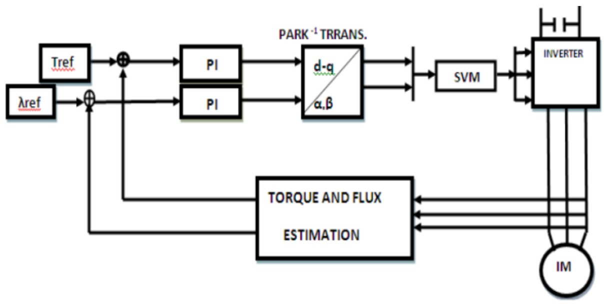

Fig -4 : Block diagram of DTC-SVM

From PI flux controller, direct axis voltage is produced and control quadrature axis voltage is from PI flux controller. These q and d axis voltages are converted into amplitude of stator voltage.Stator flux angle is calculated by using rotor angular frequency and slip angular frequency.The voltages (V_d,V_q) and stator flux angle are used as reference signals in space vector modulation.DTC based on SVM approach can be explained in detail as follows:

The output of PI torque controller is the voltage in quadrature reference frame as shown:

$$V_{sq} = K_p\left[\Delta T_e + \frac{1}{T_i}\int \Delta T_e dt\right] \quad (18)$$

$$\Delta T_e = T_{ref} - T_{est} \quad (19)$$

From PI flux controller, voltage in direct reference frame can be expressed as shown below:

$$V_{sd} = K_p\left[\Delta\lambda_e + \frac{1}{T_i}\int \Delta\lambda_s dt\right] \quad (20)$$

$$\Delta\lambda_s = \lambda_{ref} - \lambda_{est} \quad (21)$$

$$V_s = V_{sd} + jV_{sq} \quad (22)$$

By applying cartesian to polar transformation, amplitude voltage can be obtained as shown below;

$$|V_s| = \sqrt{\left[(V_{sd})^2 + (V_{sq})^2\right]} \quad (23)$$

Where,

$\lambda_{ref}, \lambda_{est}$: Reference and estimation flux respectively.

T_{ref}, T_{est} : Reference and estimation torque respectively.

The stator flux angle is calculated based on the relationship between errors of torque and stator angular frequency. The slip angular frequency is the output of PI torque controller and it can be expressed as:

$$W_{si} = k_p \left[\Delta\tilde{T}_e + \frac{1}{T_i}\int \Delta\tilde{T}_e \, dt\right] \quad (24)$$

Stator angular frequency can be obtained by adding slip angular frequency with rotor angular frequency that can be expressed as :

$$W_s = W_{si} + W_r \quad (25)$$

Stator flux angle can be obtained by integrating stator angular frequency

$$\rho_s = \int W(s)dt \quad (26)$$

By applying polar to Cartesian on both amplitude voltages in Eq. (23) and stator fux angle in Eq. (26),stator voltages in direct and quadrature reference frame are generated as :

$$V_{sd1} = |V_s| \cos \rho_s \quad (27)$$

$$V_{sq1} = |V_s| \sin \rho_s \quad (28)$$

By substracting the voltages of stator flux estimation from the voltages above in Eq. (27) and (28),the error voltages in d-q reference frame can be derived.

$$\Delta V_{sd} = V_{sd1} - V_{sd\,(estimation)} \quad (29)$$

$$\Delta V_{sq} = V_{sq1} - V_{sq\,(estimation)} \quad (30)$$

$$V_{sd\,(new)} = \Delta V_{sd} + R_s i_{sd} \quad (31)$$

$$V_{sq\,(new)} = \Delta V_{sq} + R_s\, i_{sq} \quad (32)$$

Here, the control system is based on Space Vector Modulation(SVM), amplitude of voltage in direct-quadrature reference frame and angle of stator flux. Reference torque and the estimated torque is applied to the input of PI torque controller so that control quadrature axis voltage is determined.Direct axis voltage is generated from flux calculator.By applying polar to Cartesian on amplitude voltage and stator flux angle, direct and quadrature voltages are generated. The reference stator voltages in d-q are calculated based on forcing the stator voltage error to zero at next sampling period. Stator voltages in αβ frame are generated by applying inverse park transformation on d-q voltages in Eq. (31) and (32) and apply to SVM. From the output of SVM, motor control signal is generated and speed of the induction motor is regulated towards rated speed.

4. FUZZY LOGIC SVM-DTC FOR IM

Fig. 5 shows basic fuzzy logic control strategy. The classical PI regulators of flux and torque were replaced by two fuzzy logic controllers.The stator flux and torque references are compared with the values calculated in flux and torque estimator and the corresponding errors are sent to the Direct Torque Fuzzy Controllers of the voltage inverter stage control system.Error and change in error acts as inputs to fuzzy logic controllers.

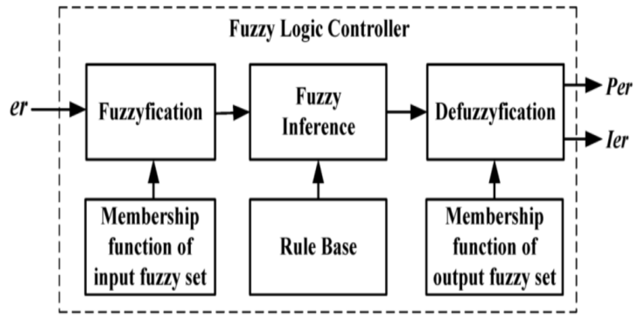

Fig.-5: Fuzzy basic model

Fuzzy set comprises from a membership function which could be defined by parameters. The value between 0 and 1 reveals a degree of membership to the fuzzy set. The process of converting the crisp input to a fuzzy value is called "fuzzification".The output of fuzzifier module is interfaced with the rules. The basic operation of Fuzzy Logic Controller (FLC) is constructed from fuzzy control rules utilizing the values of fuzzy sets in general for the error and the change of error and control action. The results are combined to give a crisp output controlling the output variable and this process is called as "DEFUZZIFICATION".

The proposed fuzzy based SVM-DTC method consists of fuzzy logic torque and flux controllers that produces optimum control vector by using instantaneous flux and torque errors. On this calculation, fuzzy logic controllers keep tracking of flux and torque errors and produce necessary change in stator flux vector angle for next step.Linguistic terms for error are defined in Table 1. Then, calculated optimum vector angle is applied to space vector pulse width modulation block(SV-PWM) and generates switching signals.

Table-1:Linguistic variables for error

Linguistic Variable	Symbol
Negative Big	NB
Negative Medium	NM
Negative Small	NS
Zero Error	ZE
Positive Small	PS
Positive Medium	PM
Positive Big	PB

Fuzzy logic control rules are defined in Table 2 that produces output from fuzzy logic flux and torque controllers used as the reference stator voltage components that are delivered to inverter stage SVM.

Table-2: Rules of Fuzzy logic controller

Δe(t)/e(t)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

5. SIMULATION AND RESULTS

A numerical simulation has been carried out in MATLAB/SIMULINK for the proposed scheme.The flux and torque loops of the drive were designed and simulated using fuzzy logic control techniques.

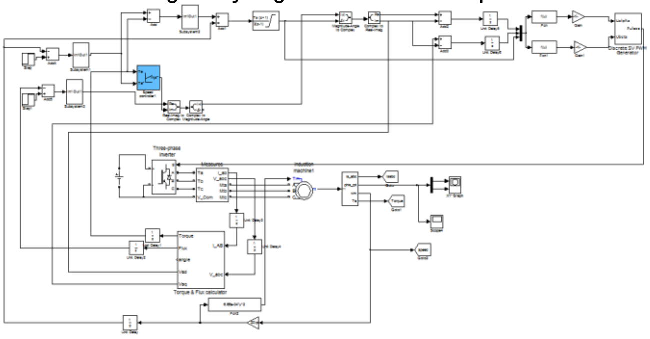

Fig-6 : Simulink model of Fuzzy based SVM-DTC

For the simulation, 3-phase Y-connected, 2.2 kW, 4-pole, 420V, 50Hz, 150 rad/sec and 5.2A induction motor AC drive system is used. Reference torque is the output of speed regulator with sampling time period of 50 μs and reference flux is 0.9Wb. The parameters are listed in Table-3.

Table-3:Induction Motor simulation parameters

Parameter	Reference Value
Frequency	50 Hz
Stator resistance(Rs)	2.5 ohms
Rotor resistance(Rr)	2.4 ohms
Flux	0.9 wb
Mutual inductance(Lm)	0.085 mH
Power	2.2 kw
Voltage	420 v
current	5.2 A
Speed	150 rad/sec
Poles	4

The simulink model with SVM- DTC is studied. The results of both SVM- DTC and proposed fuzzy based SVM-DTC in terms of speed, torque and flux and current are compared and is shown below.

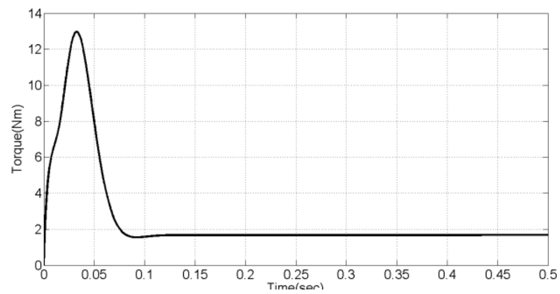

Fig-7 : Electromagnetic torque in SVM-DTC

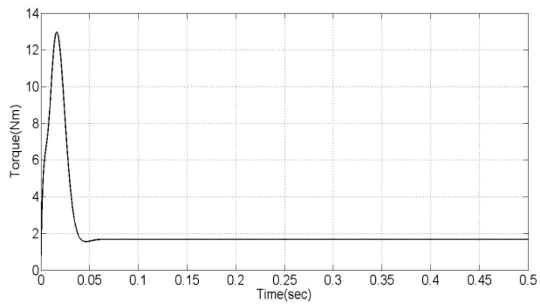

Fig-8 : Electromagnetic torque in Fuzzy based SVM-DTC

From Fig. 7 and 8, it can be noted that the ripple of torque in proposed method at low speed (50 rad/sec) is reduced with fast response and reaches steady state with in 0.1 sec when compared with fuzzy based SVM-DTC.

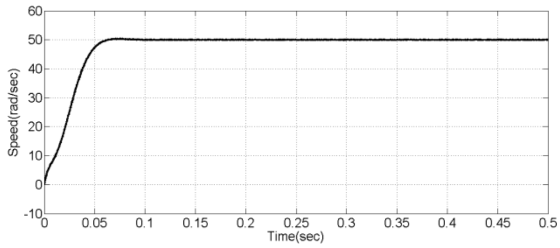

Fig-9 : Rotor speed in SVM-DTC

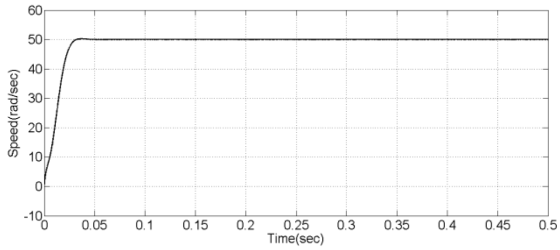

Fig-10 : Rotor speed in Fuzzy based SVM-DTC

In SVM-DTC, the rotor speed reaches the steady state within 60ms as shown in Fig. 9 but the rotor speed in fuzzy based SVM-DTC reaches the steady state value within 30 ms as shown in Fig. 10. The control of speed gives fast dynamic response with no overshoot by using fuzzy logic control technique.

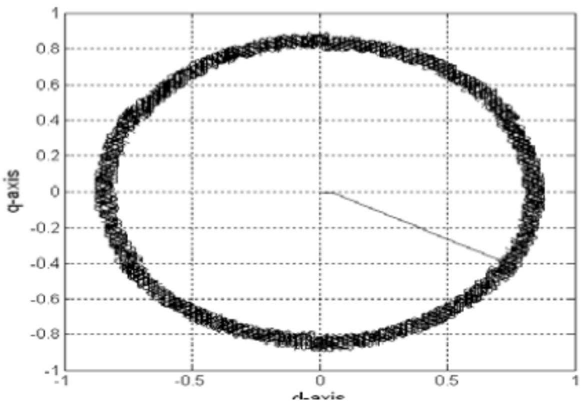

Fig-11 : Stator flux in SVM-DTC

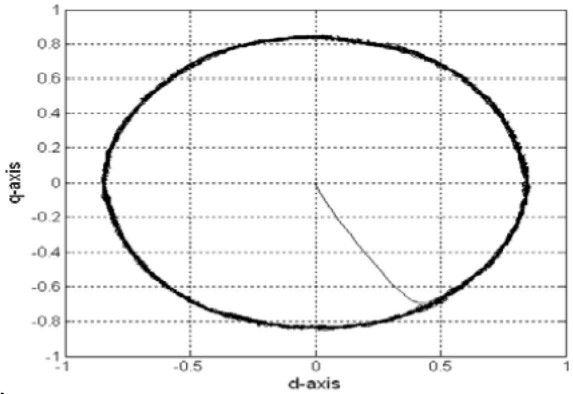

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Fig-12 : Stator flux in Fuzzy based SVM-DTC

Stator flux in SVM-DTC as shown in Fig . 11 maintains circular orbit but with high ripple but the ripple of flux in fuzzy based SVM-DTC is reduced as shown in Fig. 12.

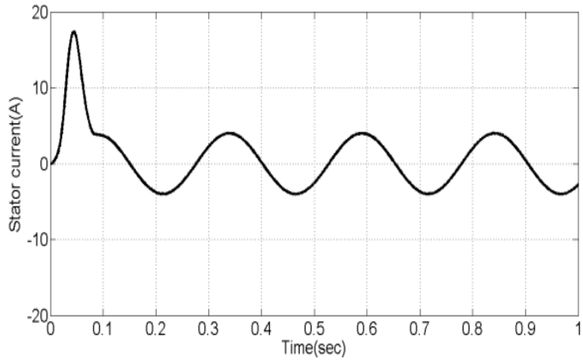

Fig-13 : Stator current in SVM-DTC

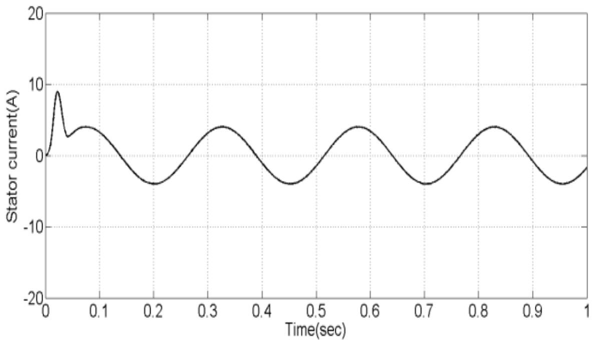

Fig-14 : Stator current in Fuzzy based SVM-DTC

The stator current of combined SVM-DTC suffers from distortion which cause increasing harmonics that degrade the system performance comparing with fuzzy based SVM-DTC as shown above(Fig. 13 and 14).Total Harmonic Distortion(%THD) is significantly reduced to 25% in fuzzy based SVM-DTC when compared with 75% of SVM-DTC. Finally, the transient and steady state response of an induction motor can be greatly improved by using fuzzy logic flux and torque controllers.

6. CONCLUSION

In this paper, the design of a fuzzy logic based s pace vector modulation technique is proposed for the DTC controlled induction motor drive. The results are analysed, designed and the system performance was studied extensively. Results prove that it is the efficient method to provide torque and flux control without changing motor parameters.

The simulation results showed that the proposed method procures good performance in presence of load disturbances as it combines space vector modulation and fuzzy logic control techniques; the advantages of this combination are fast response,reduced ripples in flux and constant switching frequency.This technique can be applied for AC drives where high dynamic performance is required and can be done practically by using Digital Signal processing(DSP) board.

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