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Improved Steady State and Transient State Torque /Speed Response of Induction Motor Using Fuzzy Logic Controller

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Abstract: Aims to presents a Space Vector-PWM based Direct Torque Control (DTC) of the three-phase Induction Motor using a Fuzzy Logic Controller (FLC) for good speed regulation and lower electromagnetic torque ripples. Induction Motor has a three phase winding with the operating frequency of 50/60Hz and the operating voltage of 230VAC. DTC is achieved by comparing the motor actual torque and operating flux with the motor reference electromagnetic torque and flux values directly. Conventional method uses the Indirect Vector Control (IVC) method and static PI controller in a speed regulation loop to generate the flux reference and torque reference values. The main drawback of the conventional system is that the effect of spiky torque in the motor is forced to draw a higher current especially, when we have load torque which has to be applied for certain time and then switched off and so on and if the motor is overloaded (even for short time) the situation becomes more dangerous and the protection system may work to disconnect the unit and high stator flux and the speed of Induction motor is reducing under transient and dynamic state of operating condition. These drawbacks were reduced in proposed DTC method. In proposed method, the static PI controller is replaced by the Fuzzy Logic Control. Fuzzy logic speed controller generates the torque reference value and flux reference value based on the speed error. The proposed method is implemented using MATLAB/SIMULINK version R2011a.

Keywords: FLC- based DTC, IGBT based inverter, PI-Speed controller, Low torque ripples, dynamic response

I. INTRODUCTION

The induction motor is one of the most widely used machines in industrial applications due to its high reliability, relatively low cost and modest maintenance requirements. However, induction motor control is a more complex problem as its model is multivariable and highly nonlinear dynamics. Furthermore, the model parameters are time-varying during the normal operation and most of the state variables are note measurable.

The most popular method was used V/F constant. However, the fast torque responses precise operation in every speed region, absence of sensors and self tuned controller has become the main property of variable speed drives. Induction motor control has been deal with following different approaches. These includes simple linear techniques such as Field Oriented Control (FOC), Direct Torque Control (DTC) and more involved nonlinear techniques like input-output linearization, Back-stepping, passivity, sliding mode. In vector control method, stator current both magnitude and phase angle are simultaneously controlled. Vector control improves the dynamics performance of the Induction motor. During acceleration, deceleration and speed reversal operation of the motor, the speed and torque value are controlled with low ripples. But the vector control method has some drawback, such as it requires two coordinate transformations (Clark-Park transformation and Inverse Clark-Park transformation), current controller for controlling torque producing current and flux producing current and high motor's parameter sensitivity.

These drawbacks were eliminated in proposed DTC control method. DTC doesn't require co-ordinate transformation system and motor torque and flux values are directly calculated from the powerful motor mathematical model. In this proposed DTC method SV-PWM technique is used for controlling the inverter output voltage magnitude and phase. Hysteresis controller is employed for torque and flux control. The main feature of the DTC is simple structure and good dynamic behaviour. It improves the motor static speed accuracy, dynamic speed accuracy, torque response and speed response [1-4].

II. PRINCIPLE OF OPERATION OF PROPOSED SCHEME

The basic block diagram of DTC is shown in Fig.1. In DTC the actual parameters are controlled directly. Here the control variables are motor magnetizing flux and electromagnetic torque. Like a dc machine, Independent speed control and torque control is possible in this scheme [5].

The fuzzy logic control is one of the controllers in the artificial intelligence techniques. Fig. 1(a) shows the schematic model of the DTC of Induction Motor Drive (IMD) using Fuzzy Logic Controller (FLC) based PI controller for Speed ripples and torque ripple controls. In this project, Mamdani type FLC is used and the DTC of IMD using conventional PI-Speed controller requires the precise mathematical model of the system and appropriate gain values of PI controller to achieve high performance drive.

Therefore, unexpected change in load conditions would produce overshoot, oscillation of the IMD speed, long settling time, high torque ripple, and high stator flux ripples. To overcome this problem, a fuzzy control rule look-up table is designed from the performance of torque response of the DTC of IMD. According to the speed error and change in speed error, the proportional gain values are adjusted on-line as shown in Fig. 1(b).

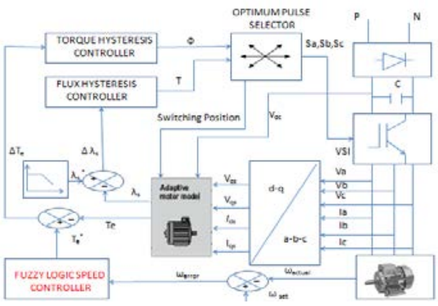


Fig. (a)

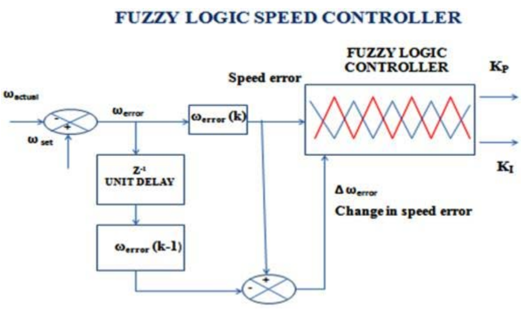


Fig. (b)

Fig.1. Proposed DTC scheme (a) Schematic diagram of proposed DTC Scheme. (b) Fuzzy Logic Speed Controller.

III CALCULATION OF AN ELECTROMAGNETIC TORQUE

The three phase and two level VSI is shown in Fig.3, it has a six switches namely S1, S2…S6. Eight possible voltage space vectors (V0-V7) are achieved by suitable switching position of the Inverter. In eight voltage space vectors, V1 to V6 is active voltage vector and V0, V7 are zero voltage vectors [6-7].

In VSI, the switches S1, S2, S3 are called upper switches and S4, S5, S6 are called lower switches. When the upper part of switches is ON, then the switching value is „1" and when the lower switch is ON, then the switching value is „0" according to the combination of the switching modes are Sa, Sb, and Sc.

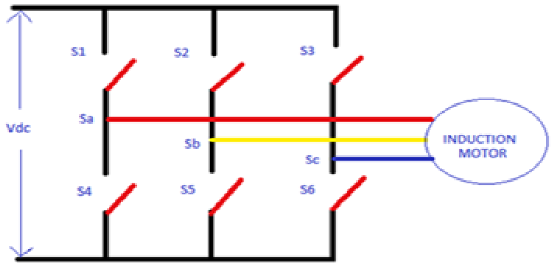


Fig.2. Schematic diagram of voltage source inverter(VSI).

The inverter output voltages are calculated from the following equation

$$V^{s} = (Vdc/3) * [2Sa - Sb - Sc] \quad (1)$$
$$V_b^{s} = (Vdc/3) * [-Sa + 2Sb - Sc] \quad (2)$$
$$V_c^{s} = (Vdc/3) * [-Sa - Sb + 2Sc] \quad (3)$$

In general, the stator voltage vector is written as in equation (1)

$$Vs = \sqrt{(2/3)} * V_{dc} * (sa + s_b * e^{j.(2\Pi/3)} + s_c * e^{-j.(2\Pi/3)}) \quad (4)$$

Where, V_{dc} is the dc link voltage of the inverter. The stator voltage and current is obtained from the following equations:

$$V_s = V_{ds}^{s} + jV_{qs}^{s} \quad (5)$$
$$i_s = i_{ds} + ji_{qs} \quad (6)$$

The inverter three-phase voltage vectors can be converted to stationary d-q axis with respect to stator frame by the following equation,

$$V_{ds}^{s} = (2/3)\, Sa + (-1/3)\, Sb + (-1/3)\, Sc \quad (7)$$
$$V_{qs} = (0)\, Sa + (-1/\sqrt{3})\, Sb + (1/\sqrt{3})\, Sc \quad (8)$$

The stator flux is calculated from the actual equivalent circuit of an Induction Motor as follows:

$$\lambda_{qs}^{s} = \int (V_{qs}^{s} - R_S.i_{qs}^{s})\, \partial t \quad (9)$$
$$\lambda_{ds} = \int (V_{ds} - Rs.i_{ds})\, \partial t \quad (10)$$
$$\lambda_s = \sqrt{\lambda_{qs}} + \lambda_{ds} \quad (11)$$

And the stator and rotor flux linkage are

$$\lambda_s^{s} = L_s I_s + I_r L_m \quad (12)$$
$$\lambda_r^{s} = L_r I_r + I_s L_m \quad (13)$$

The electromagnetic torque developed on

the motor shaft is the vector (cross) product of the stator flux and rotor flux linkage as follows

$$Te = (3/2) * (P/2) * (\lambda_r^s \times \lambda_s^s) \quad (14)$$

That is the magnitude of torque can be written as

$$Te = (3/2) * (P/2) * \lambda_r^s \lambda_s^s \sin\alpha \quad (15)$$

Where α is the angle between fluxes.

The electromagnetic torque angle is given by $\alpha = \tan^{-1} (\lambda_{ds} / \lambda_{qs})$. But the estimation of the rotor flux is somewhat difficult. So the electromagnetic torque is calculated from the stationary d-q frame with respect to stator as follows:

The Electromagnetic torque of the motor is expressed as

$$Te = 1.5*(P/2)*(i_{ds}^s*\lambda_{qs}^s - i_{qs}^s*\lambda_{ds}^s) \quad (16)$$

P is no of poles.

The glossary of symbols is summarized as follows:

d^s, q^s = Stationary reference coordinates.
V_{ds}^s, V_{qs}^s = Stator voltage in d-q coordinates.
i_{ds}, i_{qs} = Stator current in d-q coordinates.
i_{dr}, i_{qr} = Rotor current in d-q coordinates.
$\lambda_{ds}, \lambda_{qs}$ = Stator flux in d-q coordinates.
$\lambda_{dr}, \lambda_{qr}$ = Rotor flux in d-q coordinates.
L_s, L_r = Stator and rotor self-inductance. L_m = Mutual inductance.
I_m = Magnetizing current
R_s, R_r = Stator & rotor resistance.
Ω_{ref} = Reference Rotor angular speed. Ω_{actual} = Actual Rotor angular speed.
T_e^* = Reference of electromagnetic torque.
T = Actual electromagnetic torque.
λ_S^* = Reference motor flux .
λ_S = Actual motor flux.

IV. SWITCHING OF AN INVERTER

The stator rotating magnetic field position can be determined by the proper inverter switching. There are eight possible switching position achieved in the two levels VSI fed Induction motor drive. Each switching of the inverter shifts the magnetic field position 60degree from the current position. The switching position has a six active voltage position and two zero voltage position. The eight possible switching positions can be obtained from the following waveform:

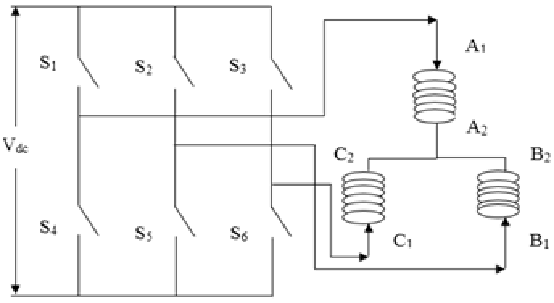


Fig.3.Three phase stator winding with VSI

Consider an Induction motor with three phase star connected stator winding. Assume that the three phase sinusoidal supply is fed from VSI to the stator winding with 120 degree phase shift irrespective of the frequency. Fig.4. Shows the Stator Rotating Magnetic field position based on the inverter switching.

When AC voltage is applied to the stator, the current flows through the phase winding. Depending upon the direction of current flow, the magnetic field is developed inside the stator. It assumes that the positive current flow through the phase windings A1, B1 and C1 result in a north pole [8-10].

Table 1.Magnetic field for induction motor phase currents

WINDING TERMINALS	WINDING CURRENT FLOW DIRECTION	
	POSITIVE CURRENT FLOW	NEGATIVE CURRENT FLOW
A1	North Pole	South Pole
A2	South Pole	North Pole
B1	North Pole	South Pole
B2	South Pole	North pole
C1	North Pole	South Pole
C2	South Pole	North Pole

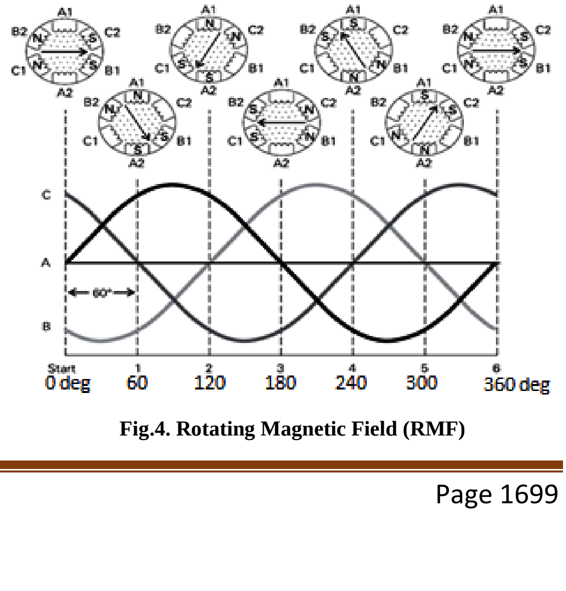


Fig.4. Rotating Magnetic Field (RMF)

V. DIRECT FLUX CONTROL

Motor actual flux is estimated from the equations (9),(10) and (11):

$$\lambda_{qs}^{s} = \int (V_{qs}^{s} - R_S.i_{qs}^{s})\, \partial t \quad (9)$$
$$\lambda_{ds} = \int (V_{ds} - Rs.i_{ds})\, \partial t \quad (10)$$
$$\lambda_s = \sqrt{\lambda_{qs} + \lambda_{ds}} \quad (11)$$

The actual motor flux is compared with the reference flux value. The flux error value is given as input to the flux hysteresis controller.

Flux error = reference flux – actual motor

$$\Delta \lambda_s = \lambda_s^* - \lambda_s \quad (17)$$

The flux error value is compared with the hysteresis flux band width ($\Delta\varphi$). The flux error value is maintained within the allowable hysteresis flux band width limit.

Hysteresis flux acceptable error value

$$\Delta\varphi = \Delta\varphi_{upper} - \Delta\varphi_{lower}$$

The output action of the flux hysteresis controller is given in the following table:

Table 2. Flux hysteresis comparator output

State	Flux Comparator output (φ)
$\Delta \lambda_s > \Delta\varphi$	1 (Increase the flux)
$\Delta \lambda_s < -\Delta\varphi$	-1(Decrease the flux)

VI. DIRECT TORQUE CONTROL

Direct torque control (DTC) technique was claimed to have nearly comparable performance with the vector controlled drives. The main features of DTC are:

- Direct control of stator flux and electromagnetic torque;
- Indirect control of stator currents and voltages;
- Approximately sinusoidal stator fluxes and stator currents;
- Reduced torque oscillations;
- Excellent torque dynamics;
- Inverter switching frequency depending on flux and torque hysteresis bands

The torque hysteresis comparator has a three level output. The actual motor torque is compared with the reference torque value. The reference torque value is generated from the PI-Speed controller based on the speed error value.

Electromagnetic torque error value

$$\Delta T_e = T_e^* - T_e \quad (18)$$

Torque hysteresis comparator acceptable error value is

$$\Delta T = \Delta T_{upper} - \Delta T_{lower} \quad (19)$$

The actual motor torque in-terms of stator flux linkages are calculated from the equation (16):

$$Te = 1.5*(P/2)*(i_{ds}^{s}*\lambda_{qs}^{s} - i_{qs}^{s}*\lambda_{ds}^{s}) \quad (16)$$

Torque angle $\alpha(k) = \tan^{-1}(\lambda_{ds}^{s} / \lambda_{qs}^{s})$ (20)

The output action of the torque hysteresis controller is given below in the table:

Table 3.Torque hysteresis comparator output

State	Torque Hysteresis comparator output (T)
$\Delta T_e > \Delta T$	1 (Increase the torque)
$\Delta T < \Delta T_e < -\Delta T$	0 (Torque at zero)
$\Delta T_e < -\Delta T$	-1(Decrease the torque)

The voltage vector is selected based on the output of the torque and flux hysteresis controller. So that the motor flux and electromagnetic torque values are maintained constant. The three digit binary number represents the switching position of VSI. The digit gives the value of Sa, Sb and Sc. The voltage vector selection is tabulated below [11-12].

Table 4.Voltage vector selection table

Hysteresis controller		Voltage sector Selection α(k)					
φ	T	α (1)	α (2)	α (3)	α (4)	α (5)	α (6)
1	1	110	010	011	001	101	100
	0	000	111	000	111	000	111
	–1	101	100	110	010	011	001
–1	1	010	011	001	101	100	110
	0	111	000	111	000	111	000
	–1	001	101	100	110	010	011

VII. MATLAB SIMULATION RESULTS OF PROPOSED DTC SCHEME

The DTC principle has been simulated using MATLAB/Simulink software. The Simulink model of the DTC scheme for SV-PWM VSI fed IM drive has been presented in Fig. 5. The parameters of the induction motor in this simulation are as follows:

Rated motor power (P_r) = 2 kVA
Rated motor voltage (V_r) = 230 V
AC Rated motor frequency (f_r) = 50 Hz
Stator resistance (R_S) = 14.85 mΩ
Rotor resistance (R_r) = 9.2 mΩ
Stator self-Inductance (L_s) = 0.3027 mH
Rotor self-inductance (L_r) = 0.3027 mH
Mutual Inductance (L_m) = 10.46 mH
Number of Poles (P) = 2
Moment of Inertia (J) = 3.1 kg*m^2
Friction Factor (F) = 0.08 N-m-s
Reference flux (λ_s^*) = 0.8 Wb

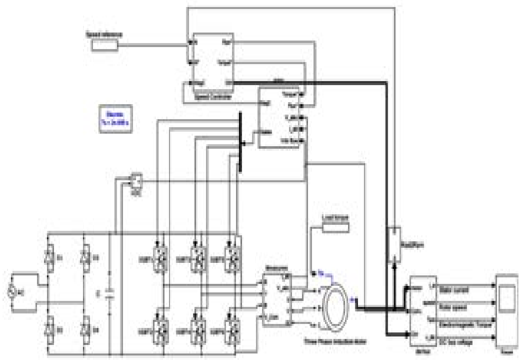


Fig.5. Simulation diagram of DTC based three phase induction motor control technique

DTC Subsystem:

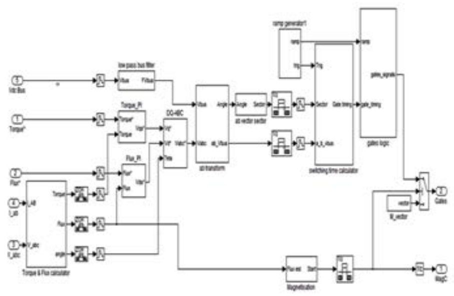
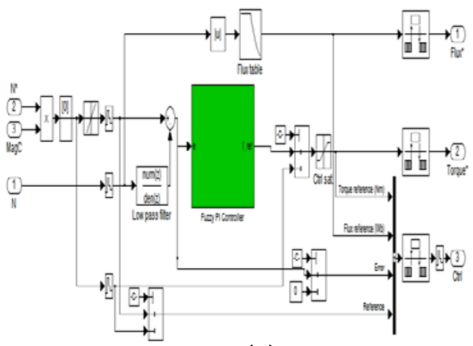
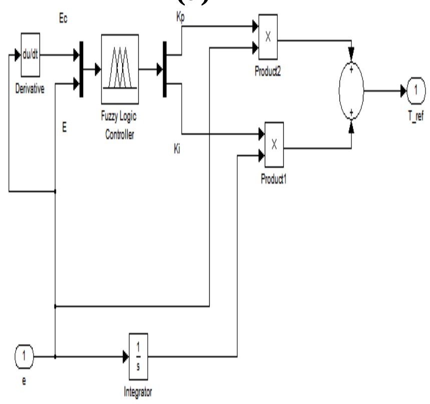


Fig.6. Simulation subsystem diagram of DTC block

Speed Controller Simulink Subsystem:



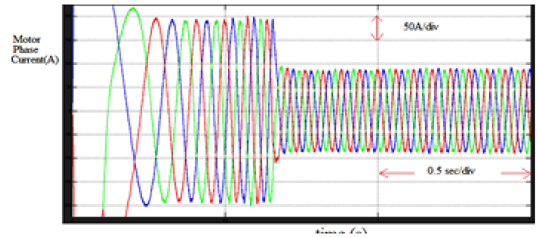
(a)



(b)

Fig.7. (a) Simulation subsystem diagram of fuzzy logic speed controller block (b) Fuzzy logic controller simulation subsystem

Simulation Waveforms of Proposed Scheme:



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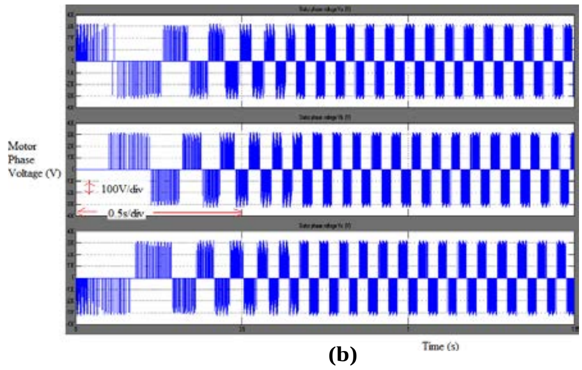

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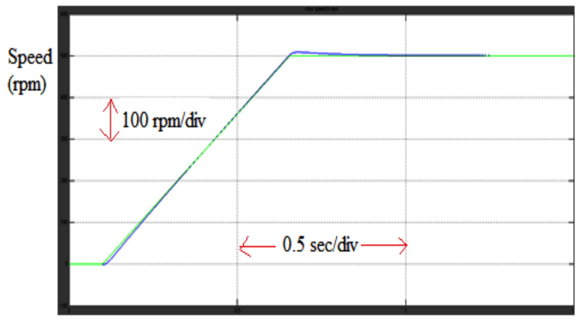
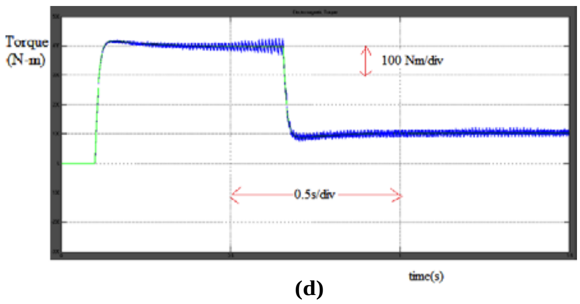
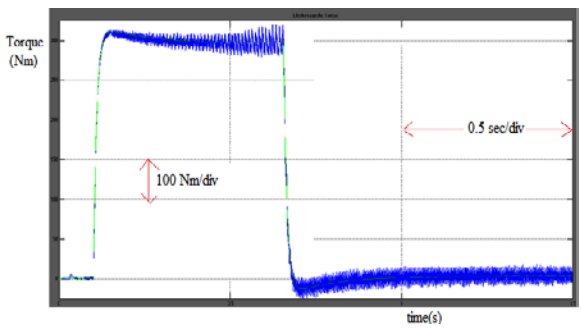
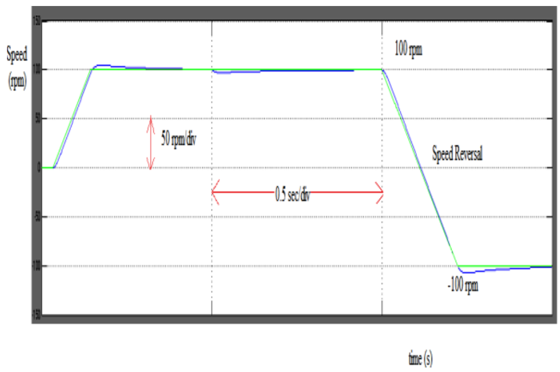


(c) time(s)

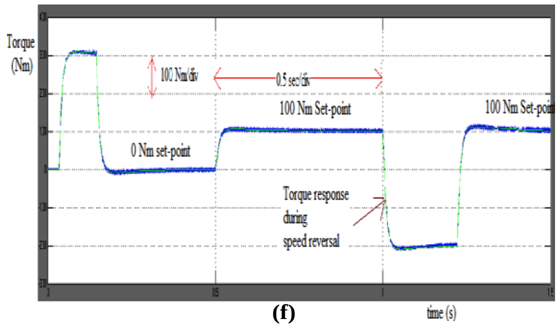


(d)

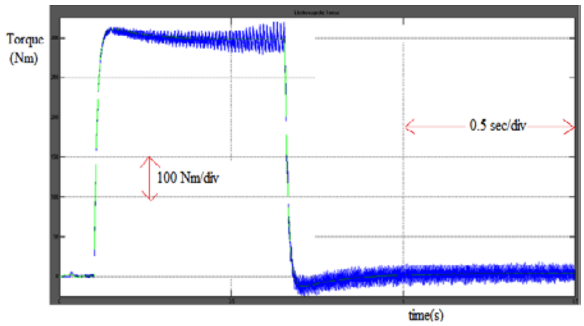




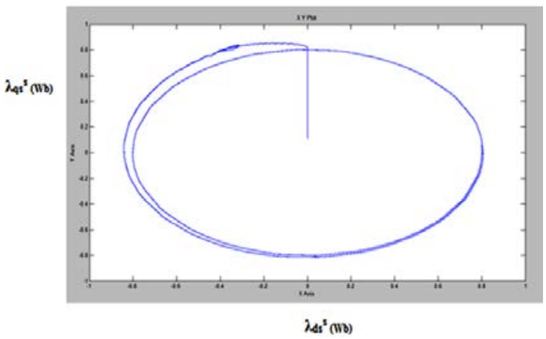
(e)



(f)



(g)



(h)

Fig.9.Simulation results (a) Motor three phase current when load torque is 100 Nm. (b) Motor three phase voltage when speed is 100 rpm. (c) Motor speed when set-speed is 500 rpm. (d) Motor torque when set-point load torque is 100 Nm. (e) Motor torque at 0 N-m set-point load torques. (f) Speed reversal from 100 rpm to -100 rpm. (g) Motor torque with different load torque set-point values and speed reversal operation. (h) Stator flux trajectory.

CONCLUSION

An effective control technique is presented for direct flux and torque control of three-phase Induction Motor. In this proposed control technique the static PI-Speed controller is replaced by Fuzzy logic controller and IVC is also replaced by DTC thereby reducing the stator flux ripples and torque ripples. The two independent torque and flux hysteresis band controllers are used in order to control the limits of the torque and flux. It is clearly seen that the locus of the stator flux of proposed scheme is within the circle boundary created by six active vectors. Whenever there is a change of stator flux, the space vector switching are such chosen that the flux error remains within the band of the controller. The simulation result of both conventional and proposed techniques had been carried out for three-phase Induction Motor. Compared to both techniques, proposed control technique is better for good speed regulator, low stator flux linkage and torque ripples under transient and dynamic state operating conditions.

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