Implementation of Direct Torque Control Scheme for Three Phase Induction Motor Drives

K.Rajesh[1], G.Arun kumar[2], D.Sathish[3]
[1]*M-Tech - Asst. Professor in Aurora's Scientific Technological & Research Academy, Hyderabad, Telangana,India*
[2]*M-Tech - Asst. Professor in Mahatma Gandhi Institute of Technology, Hyderabad, Telangana India*
[3]*M-Tech (Ph.D) - Asst. Professor in Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India*
[1]*raajeesheee0707@gmail.com,* [2]*gvlpak006@gmail.com,* [3]*data.sathish@gmail.com*

Abstract—**Induction motor drives (IMD) are currently used in many industrial applications due to its reliability, ruggedness and easier in maintenance. To reach the best efficiency of IMD, many new techniques of control have been developed in the last few years. These drives controlled with the vector control (VC) method have found wide applications in the industry. However, this control technique requires complex coordinate transformation, inner current control loop and accurate system parameters. An efficient method of induction motor control is the direct torque control (DTC). DTC method provides robust and fast torque response without such coordinate transformations, PWM pulse generation and current regulators. Moreover, DTC minimizes the use of motor parameters. This paper presents a study of DTC technique for voltage source inverter fed induction motor drives using MATLAB. Simulation results have shown the validity and high accuracy of the proposed model.**

Keywords— **Induction Motor Drives (IMD), Direct Torque Control (DTC), Vector control (VC).Introduction**

I. INTRODUCTION

Industrial loads require operation at wide range of speeds. Such loads are generally termed as variable speed drives. These drives demand precise adjustment of speed in a steeples manner over the complete speed range required. The loads may be constant torque or a function of speed. These loads are driven by hydraulic, pneumatic or electric motors. An industrial drive has some special features when driven by electric motors. Induction machines have provided the most common form of electromechanical drive for industrial, commercial and domestic applications that can operate at essentially constant speed. Induction machines have simpler and more rugged structure, higher maintainability and economy than dc motors. In contrast to the commutation dc motor, the IMD can be operated in an aggressive or volatile environment since there are no problems with spark and commutation. These advantages however are suppressed due to requirement of complex control circuit and nonlinear characteristics of the induction motor. In general, induction motor can be controlled by both open and closed loop control techniques. These are also known as scalar and vector control (VC) schemes. VC aims to control the rotor flux and torque of the motor by estimating the speed and voltage. This estimation can be either directly done through measurements or indirectly through calculations [1]. A simpler alternative to the vector control is the direct torque control (DTC).While DTC and VC have different concept of operation, they both provide an effective control of the flux and torque. The direct torque control (DTC) is the main interest of this project and it will be described in the following sections.

IMD control methods can be divided into scalar and vector control. In scalar control, which is based on relationships valid in steady state, only magnitude and frequency (angular speed) of voltage, current, and flux linkage space vectors are controlled. Thus, the scalar control does not act on space vector position during transients.

Contrarily, in vector control, which is based on relations valid for dynamic states, not only magnitude and frequency (angular speed) but also instantaneous positions of voltage, current, and flux space vectors are controlled. Thus, the vector control acts on the positions of the space vectors and provides their correct orientation both in steady state and during transients.

In the vector control the motor equations are transformed in a coordinate system that rotates in synchronism with the rotor flux vector. The torque and flux components are identified and controlled independently to achieve a good dynamic response. However there is a necessity of transforming the variables in the synchronously rotating reference frame to the stator reference frame to control actual currents/ voltages. This transformation contains trans-credential functions like sine, cosine and introduces computational complexity into the system.

The purpose of this paper is to give a short overview on DTC principle and to simulate the principle using MATLAB/SIMULINK Software. The simulation results are presented and agreed with the theory. This paper is organized as follows. Section II discusses the basics of DTC based on the hysteresis controllers for flux and torque.

Section III is devoted for the modelling of induction motor in stationary reference frame. Section IV presents Simulink implementation of DTC and the results of DTC.

The glossary of symbols is summarized as follows:

d, q = Stationary reference coordinates.
V_{ds}, Vqs = Stator voltage in d-q coordinates.

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i_{ds}, i_{qs} = Stator current in d-q coordinates.
i_{dr}, i_{qr} = Rotor current in d-q coordinates.
λ_{ds}, λ_{qs} = Stator flux in d-q coordinates.
λ_{dr}, λ_{qr} = Rotor flux in d-q coordinates.
L_{ls}, L_{lr} = Stator & rotor leakage inductance.
L_s, L_r = Stator & rotor self inductance.
L_m = Magnetizing inductance.
R_s,R_r = Stator & rotor resistance.
ω_r = Rotor speed.

II. INTRODUCTION TO DIRECT TORQUE CONTROL

A. Basics of Direct torque control:

The Direct Torque Control DTC was first introduced by Takahashi in 1984 in Japan and by Dopenbrock in 1985 in Germany and today this control scheme is considered as the world's most advanced AC Drives control technology. This is a simple control technique which does not require coordinate transformation. This is based on the theory on the Field Oriented Control of Induction machine [6] and the theory of Direct Self Control [7]. A spatial vector presentation of motor quantities is used. Flux and Current vectors and inverter voltage can be represented in stator co-ordinates as shown in Fig. 1.

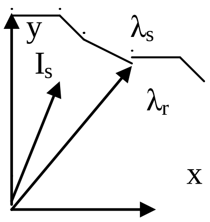

FIG. 1: Stator Flux vector movement relative to rotor flux.

The length of the stator flux is kept constant and the motor torque is controlled by means of the angle α. The rotor time constant of the standard induction motor is typically larger than 100 ms, and thus the rotor flux is stable and it changes slowly compared to stator flux. It is possible to achieve the required torque very effectively by rotating the stator flux vector directly in a certain direction as fast as possible.

The strategy of DTC is straightforward. If more torque is required the purpose of next power stage switching is to fulfill the demand. The instantaneous value of the stator flux vector is controlled in order to achieve the required more torque. It means that by applying a space non-zero voltage vectors to an induction motor, the moving direction and amplitude of stator flux will change and that by applying a space zero voltage vector to an induction machine, the movement of stator flux vector is arrested. The stator flux vector is controlled by means inverter supply voltage (as stator resistance can be neglected). The optimal switching logic defines the best voltage vector according to the actual value of torque and torque reference. Six active voltage vectors and two zero-voltage vectors are available in two-level voltage source inverter, as shown in Fig. 2.

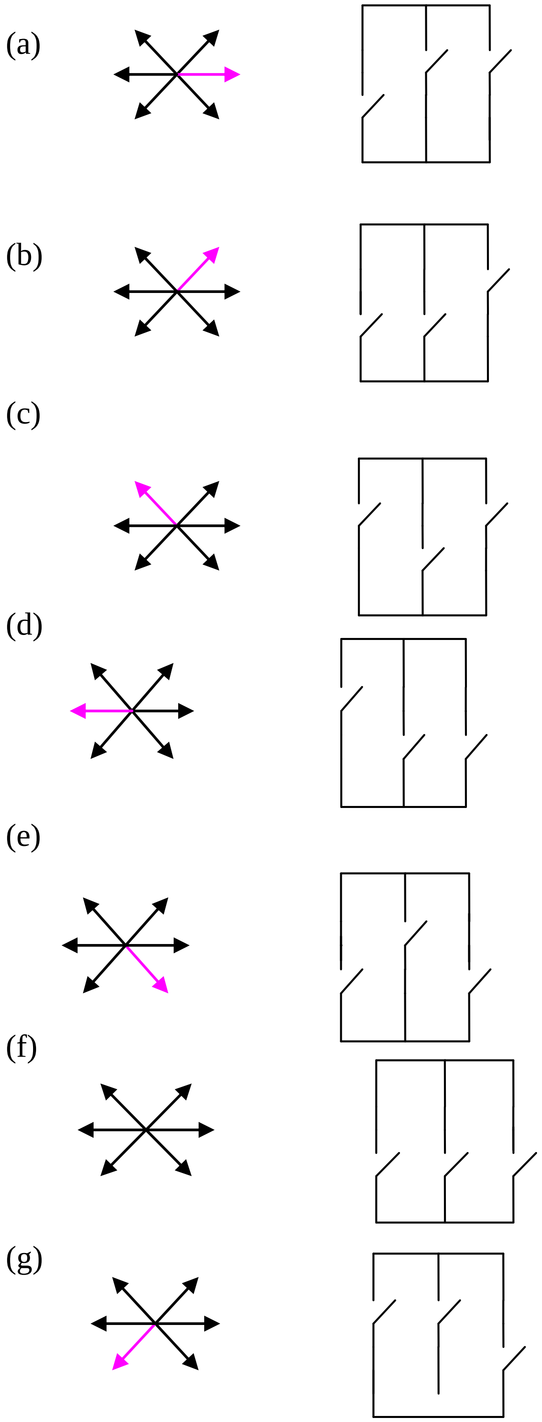

FIG. 2 (a-f): Six active vector switching, (g) Zero vector switching of inverter.

Torque is a cross product of the stator and rotor flux vectors or stator current and flux as follows:

$$Te = (3/2)\,(P/2)\lambda_r \times \lambda_s$$

That is the magnitude of torque can be written as

$$Te = (3/2)\,(P/2)\,\lambda_r\,\lambda s\,\mathrm{Sin}\alpha$$

Where α is the angle between fluxes.

2. DTC Technique using Hysteresis Torque and Flux Controller

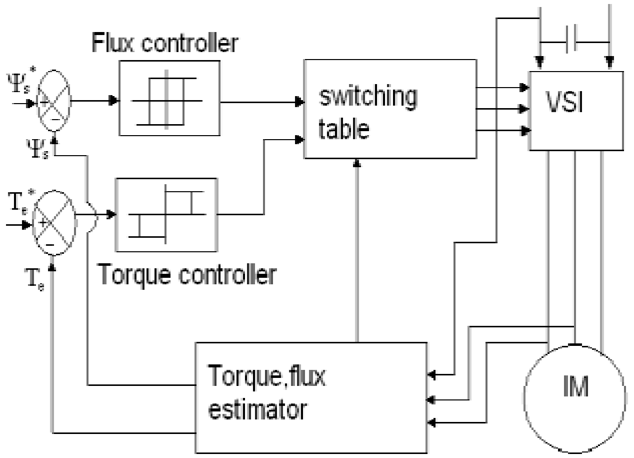

FIG. 3: The block diagram of DTC.

The block diagram of DTC scheme is shown as in the Fig. 3. This technique is based on the direct stator flux and torque control. The input voltage (Vs) and input current (Is) of the motor on the stationary reference frame can be expressed as follows:

$$V_s = V_{ds} + jV_{qs} \qquad \ldots(1)$$

$$i_s = i_{ds} + ji_{qs} \qquad \ldots(2)$$

The actual stator flux can be estimated from the equivalent circuit of the motor as follows:

$$\lambda_{qs} = \int (V_{qs} - R_S.i_{qs})\,\partial t \qquad \ldots(3)$$

$$\lambda_{ds} = \int (V_{ds} - Rs.i_{ds})\,\partial t \qquad \ldots(4)$$

$$\lambda_s = \sqrt{\lambda_{qs}^2 + \lambda_{ds}^2} \qquad \ldots(5)$$

Where λ_s is the stator flux vector and R_S is the stator resistance. The Electromagnetic torque of the motor is

$$Te = 1.5*(P/2)*(i_{ds}*\lambda_{qs} - i_{qs}*\lambda_{ds}) \qquad \ldots(6)$$

P is no of poles.

The control command for the system is speed. The Flux reference can be calculated based on the speed. Below the rated speed, rated flux is used as a reference (constant torque region). Above the rated speed; flux-weakening method generates the flux reference (constant power region). The reference flux is selected, proportional to the inverse of the reference speed. The reference torque can be calculated using the difference between reference speed and instantaneous speed (using a PI controller). Selection of such reference speed improves the dynamic response of the torque and flux control.

The command stator flux and torque values are compared with the actual values in hysteresis flux and torque controllers, respectively. The flux controller is a 2-level while the torque controller is 3-level comparator. The digitized output signals of the flux ($d\psi$) and torque (dm) controllers are as follows:

$$d\psi = 1 \text{ for } E\psi > +H\psi$$

$$d\psi = 0 \text{ for } E\psi < -H\psi$$

$$dm = 1, \text{ for } E_{Te} > +H_m$$

$$dm = -1, \text{ for } E_{Te} < -H_m$$

$$dm = 0, \text{ for } -H_m < E_{Te} < +H_m$$

Where, $E\psi$ and E_{Te} are the flux and torque errors. And $H\psi$ and H_m are the acceptable predefined torque errors, respectively.

The digitized variables $d\psi$, dm and stator flux sector S, obtained from the angular position $\gamma_s = \arctan(\lambda_{qs}/\lambda_{ds})$ [where $-(\Pi/6) + (1 - S)(\Pi/3) < \gamma_s(S) < -(\Pi/6) - (1 - S)(\Pi/3)$ defines the stator flux position over six regions of motor controlling (60^o)]. The stator input voltages are evaluated in order to determine the stator voltage vector. Having the control strategy (switching pattern), the stator voltage vector can be directly calculated as follows:

$$Vs = \sqrt{(2/3)}\,V\,(sa + s_b.e^{j.(2\Pi/3)} + s_c.e^{-j.(2\Pi/3)})$$

Where V is the inverter supply voltage (DC link voltage), and s_a, s_b and s_c are numbers 0 or 1 that are the output of switching table. In Table 1, the three digit numbers define the switching algorithm where the digits from left to right give values of s_a,s_b and s_c, respectively.

TABLE 1: Voltage Vector Table.

ψ	*Dm*	*S(1)*	*S(2)*	*S(3)*	*S(4)*	*S(5)*	*S(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

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	–1	001	101	100	110	010	011

III MODELING OF INDUCTION MOTOR

One of the major differences between FOC and DTC control is the modeling of the motor. In FOC the motor is modeled in synchronously reference frame i.e. $\omega = \omega_{e,}$ while in DTC it is in stationary reference frame i.e. $\omega = 0$.

To simulate the dynamics of the induction machine, the basic mathematical model given in Krause [2] is used. The basic mathematical model of the induction machine is derived from the Fig. 4 and is rewritten as below:

$$V_{qs} = R_S\, i_{qs} + \omega.\lambda_{ds} + \partial\lambda_{qs}/\partial t \qquad \ldots (7)$$

$$V_{qr} = R_r i_{qr} + (\omega - \omega_r)\lambda_{dr} + \partial\lambda_{qr}/\partial t \qquad \ldots (8)$$

$$V_{ds} = R_S i_{qs} - \omega\, \lambda_{qs} + \partial\lambda_{ds}/\partial t \qquad \ldots (9)$$

$$V_{qr} = R_r i_{dr} - (\omega - \omega_r)\lambda_{qr} + \partial\lambda_{dr}/\partial t \qquad \ldots (10)$$

$$Te = 1.5*(P/2)*(i_{ds}*\, \lambda_{qs} - i_{qs}*\, \lambda_{ds}) \qquad \ldots (11)$$

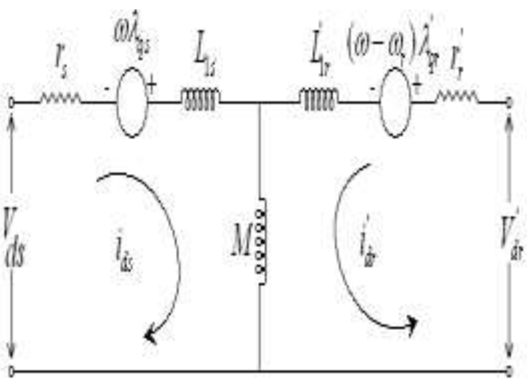
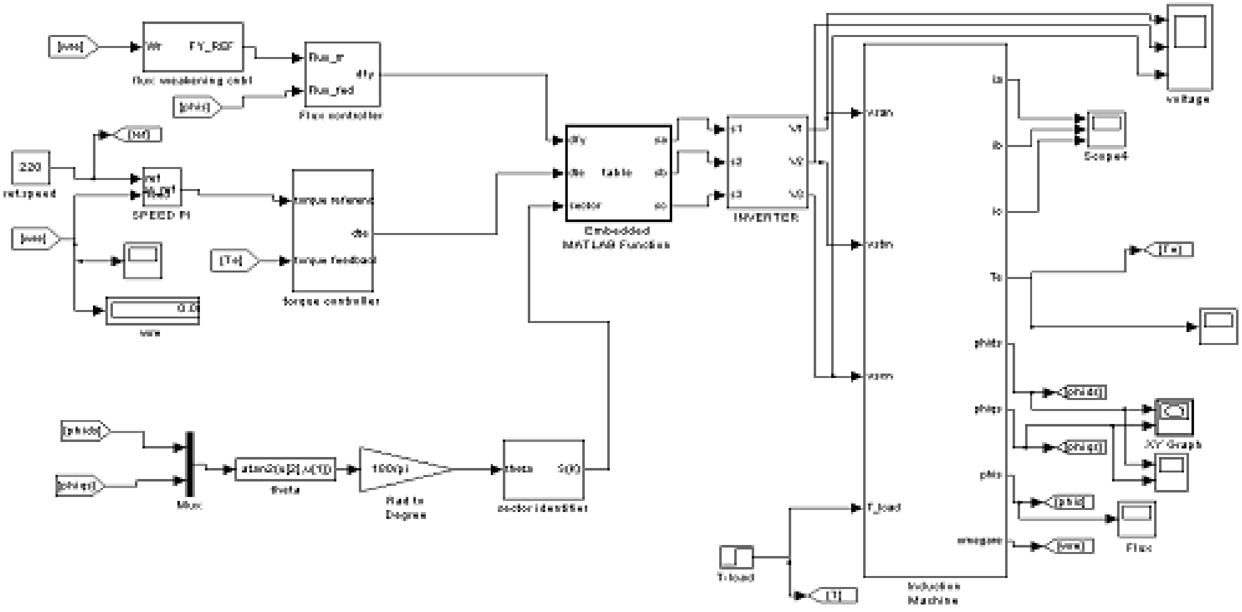


FIG. 4: Equivalent Induction Machine circuit at d-q reference frame.

IV MODELLING OF INDUCTION MOTOR DRIVE & RESULTS

The DTC principle has been simulated using MATLAB/Simulink software (version 7. 0. 1). The Simulink model of the DTC scheme for PWM VSI fed IM drive has been presented in Fig. 5.

The phase voltages of induction motor are shown in Fig.6. and phase currents of it are observed in Fig.7.The torque response and stator flux response are shown in Fig.8 and Fig.9.The rated torque response and speed response are shown in Fig.10 and Fig.11.



Direct Torque & Flux Control Of 3 phase Induction motor.
Motor Parameters:
Ls=Lr=0.21H,Lm=0.2025H,Rs=2.15ohm,Rr=2.33ohm,ref.Flux=0.7wb,ref speed=220 rad/sec,J=0.14 kg-cm*cm,P=4

FIG.5. Simulink Model of DTC scheme

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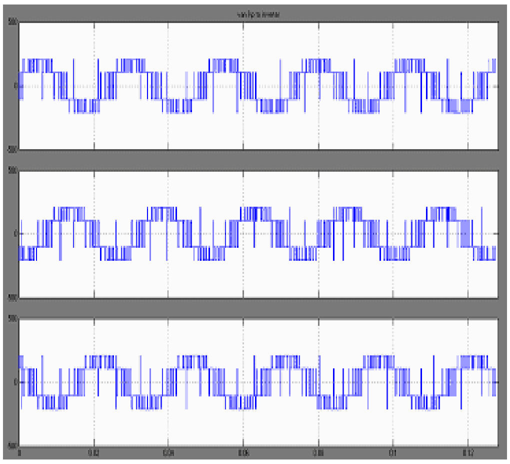

FIG. 6: Phase voltages of IM

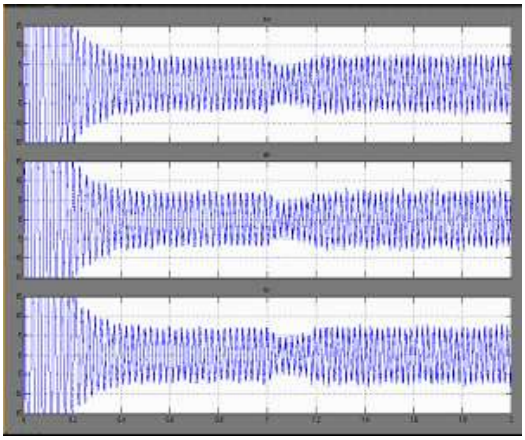

FIG. 7: Phase currents of IM

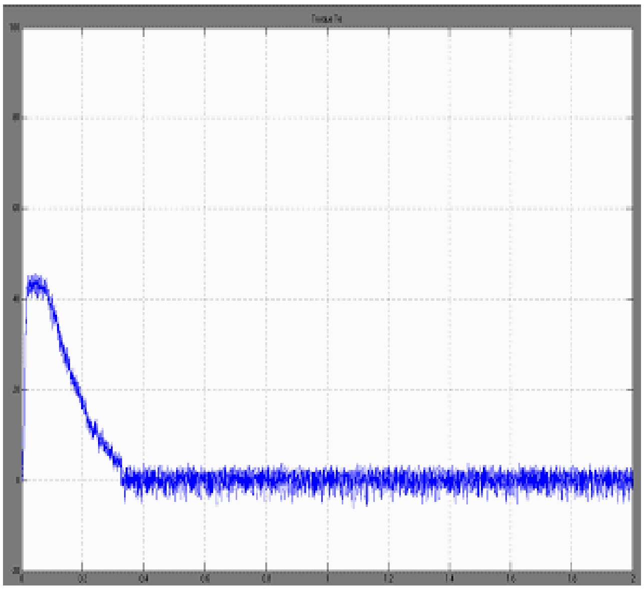

FIG. 8: Torque response for TL=0 NM.

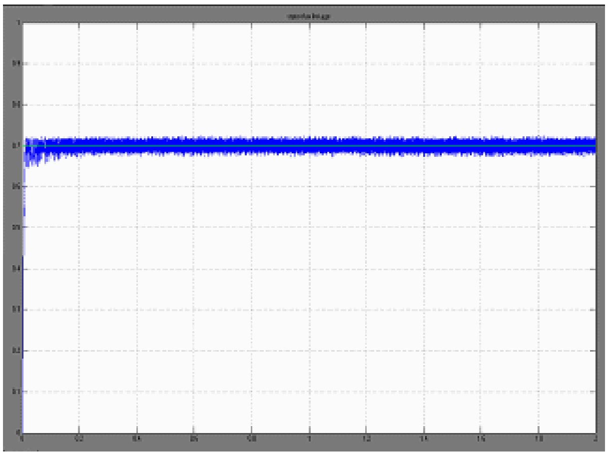

FIG. 9: Stator flux response (Ref Flux=0.7wb)

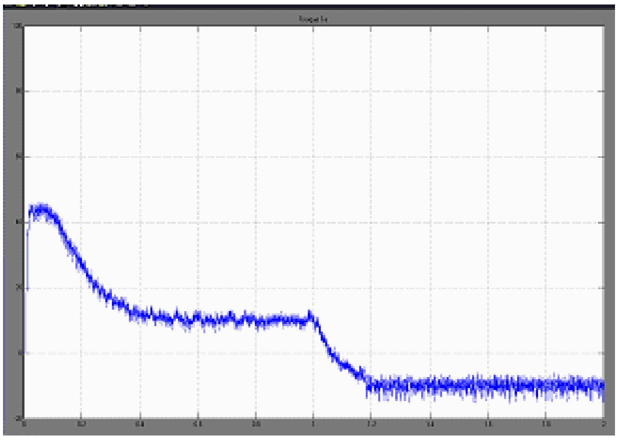

FIG. 10: Torque Response for rated Torque reversal

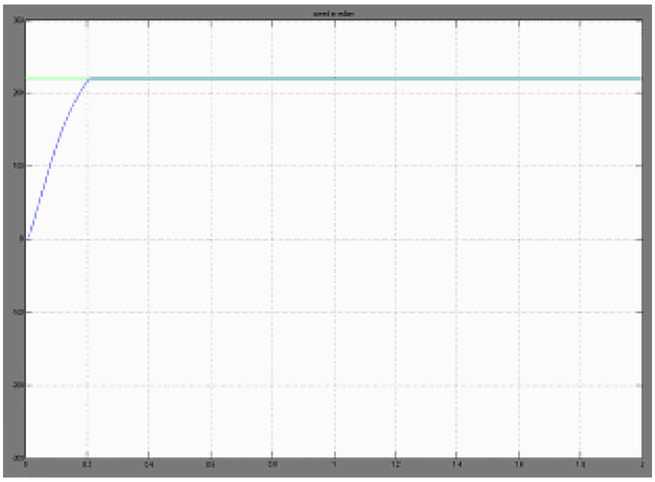

FIG. 11: Speed response in rad/sec (Speed ref = 220 rad/sec)

V. CONCLUSION

The direct torque & flux control for three phase induction motor has been proposed and simulated in this paper. The simulation results agree with the basic principles of the technique.

The locus of the stator flux is within the hexagon boundary created by six active vectors. Whenever there is a change of flux, the space vector switching are such chosen that the flux error remains within the band of the controller. DTC has the advantage of not requiring the speed or position encoders and uses the voltage and current measurements only. The torque response during no-load and torque reversal condition proves the basic principle of DTC. Therefore, further development is required to control the starting up stator current in order to protect the machine and power electronics devices.

VI. PARAMETERS USED FOR SIMULATION

R_S = 2.15 ohm.
R_r = 2.33 ohm.
L_S = 0.21 Henry.
L_r = 0.2025 Henry.
Lm = 0.2025 Henry.
P = Number of Poles = 4.
J = Moment of Inertia = 0.14.
B = Friction Coefficient = 0.0.
Ref. flux = 0.7wb.

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BIOGRAPHIES

K.Rajesh[1]
M.Tech,Asst.Professor,
Department of EEE,
AURORA’S Scientific Technological & Research Academy
Hyderabad,India.
E-mail:raajesheee0707@gmail.com.
Mobile: +91-9581532320

G.Arun kumar[2]
M.Tech,Asst.Professor,
Department of EEE,
Mahatma Gandhi Institute of Technology,
Hyderabad,India.
E-mail: gvlpak006@gmail.com.
Mobile: +91-9885450221

D.Sathish[3]
M.Tech(Ph.D),
Asst. Professor,
Department of EEE,
Chaitanya Bharathi Institute of Technology,
Hyderabad, India.
E-mail: data.sathish@gmail.com
Mobile: +91-9492433934.