Development & Implementation of Direct Torque Control for Three Phase Induction Motor Drives

Tapajit Ghosh[#1], Suman Debnath[#2], Priyanath Das[#3]

#1 Agartala, West Tripura, 9774426686
#2 Agartala, West Tripura, 9774057961
#3 Agartala, West Tripura, 94365 41700

ABSTRACT

Induction Motors (IM) has always been preferred for its reliability, ruggedness and easier in maintenance. The IM drives controlled with the vector control method has found wide acceptance in the industry. However, this control technique requires complex coordinate transformation, inner current control loop and accurate system parameters. The direct torque control (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. The Simulink model and results that validates the DTC principle has been presented. This paper proves that DTC technique is easier to implement and keeps the variable within the range.

Key words: Induction Machine (IM), Field Oriented Control (FOC), Direct Torque Control (DTC).

Corresponding Author: Tapajit Ghosh
INTRODUCTION

The Induction Motor (IM), thanks to its well known advantages of simple construction, reliability, ruggedness, and low cost, and has found wide spread industrial application. In contrast to the commutation dc motor, the IM 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 IM. IM 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. In the mid 1980s, there appeared

innovative studies of Depenbrock and of Takahashi and Noguchi, which depart from the idea of coordinate transformation and the analogy with dc motor control. This control strategy is commonly referred to as Direct Torque Control (DTC) and it has been continuously developed and improved by many other researchers. 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 principle of DTC based on the hysteresis controllers for flux and torque. Section III is devoted for the modeling 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.
    Vds, Vqs= Stator voltage in d-q coordinates.
    ids, iqs = Stator current in d-q coordinates.
    idr, iqr = Rotor current in d-q coordinates.
    λds, λqs = Stator flux in d-q coordinates.
    λdr, λqr = Rotor flux in d-q coordinates.
    Lls, Llr = Stator & rotor leakage inductance.
    Ls, Lr = Stator & rotor self inductance.
    Lm= Magnetizing inductance.
    Rs,Rr = Stator & rotor resistance.
    ωr= Rotor speed.

BASIC CONCEPTS OF DTC
Basic Principles of DTC

The Direct Torque Control 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. 2. Six active voltage vectors and two zero-voltage vectors are available in two-level voltage source inverter, as in Fig. 3.
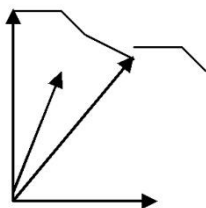

FIG. 2: Stator Flux vector movement relative to rotor flux.

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

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

Where α is the angle between fluxes. 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 fulfil 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.
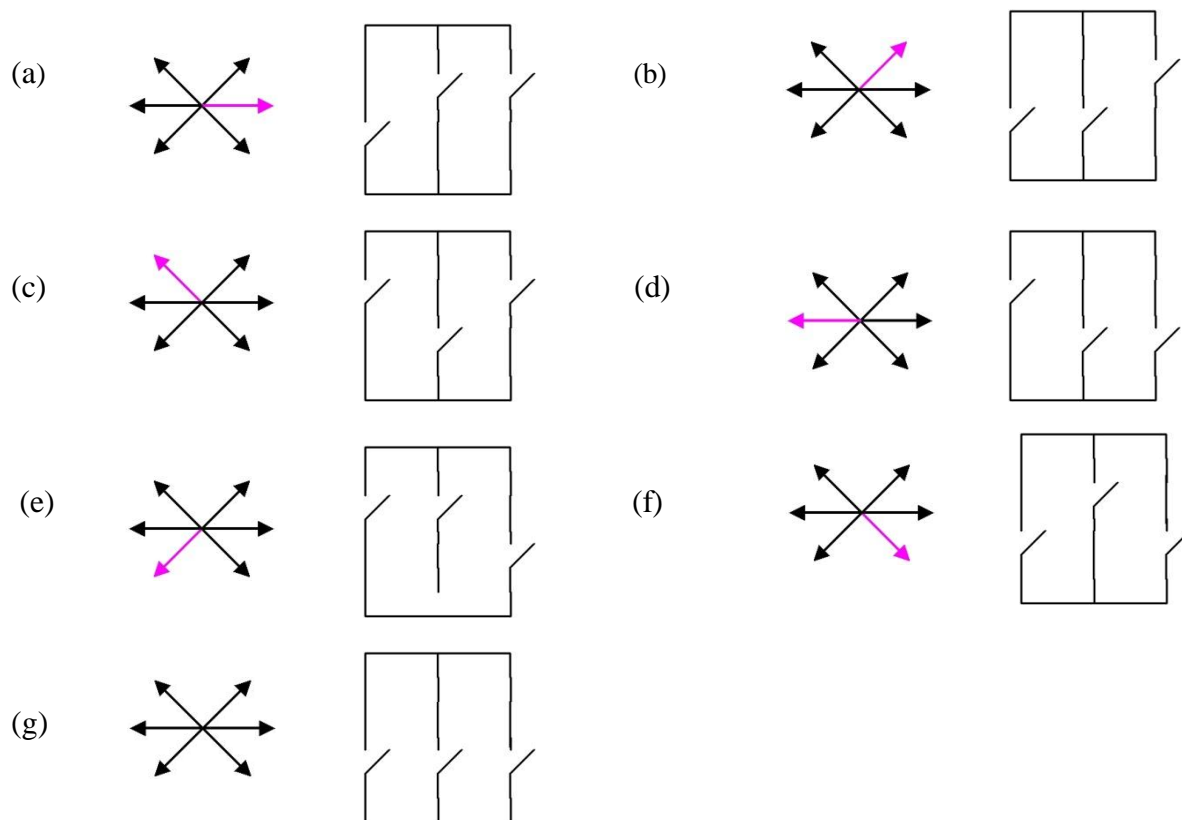

FIG. 3 (a-f): Six active vector switching, (g) Zero vector switching of inverter.

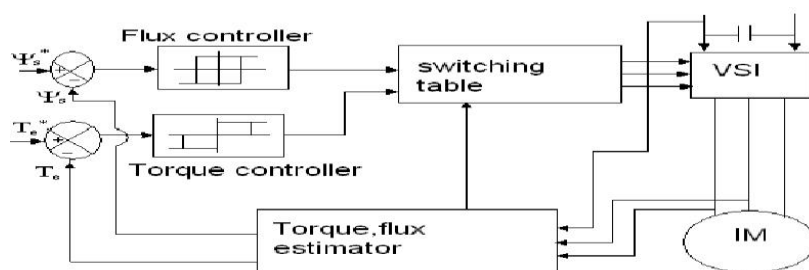## DTC Technique using Hysteresis Torque and Flux Controller

FIG. 4: The block diagram of DTC.

The block diagram of DTC scheme is shown as in the Fig. 4. 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:

Vs = Vds + jVqs

is = ids + jiqs

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

$\lambda qs = \int (Vqs - RS.iqs)\, \partial t$ ...(3)

$\lambda ds = \int (Vds - Rs.ids)\, \partial t$ ...(4)

$\lambda s = \sqrt{\lambda qs^2 + \lambda ds^2}$ ...(5)

Where λs is the stator flux vector and RS is the stator resistance. The Electromagnetic torque of the motor is

Te = 1.5*(P/2)*(ids* λqs – iqs* λds)   … (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 (dψ) and torque (dm) controllers are as follows:

dψ = 1 for Eψ > +Hψ

dψ = 0 for Eψ < –Hψ

dm = 1, for E Te > +Hm

dm = –1, for E Te < –Hm

dm = 0, for –Hm <E Te < +Hm

Where, Eψ and ETe are the flux and torque errors. And Hψ and Hm are the acceptable predefined torque errors, respectively. The digitized variables dψ, dm and stator flux sector S, obtained from the angular position γ s = arctan ($\lambda qs/\lambda ds$) [where –(Π/6) + (1 – S)(Π/3) <γs(S) < – (Π/6) – (1 – S)(Π/3) defines the stator flux position over six regions of motor controlling (60o)]. 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 + sb.e j. (2Π/3) + sc.e –j. (2 Π/3))

Where V is the inverter supply voltage (DC link voltage), and sa, sb and sc 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 sa,sb and sc, respectively.

TABLE 1: Voltage Vector Table.

ψ	dm	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
	1	110	010	011	001	101	100
1	0	000	111	000	111	000	111
	–1	101	100	110	010	011	001
	1	010	011	001	101	100	110
–1	0	111	000	111	000	111	000
	–1	001	101	100	110	010	011

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. ω = ωe, while in DTC it is in stationary reference frame i.e. ω = 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. 5 and is rewritten as below:

$$V_{qs} = R_S i_{qs} + \omega.\lambda_{ds} + \partial\lambda_{qs}/\partial t \qquad \dots (7)$$
$$V_{qr} = R_r i_{qr} + (\omega - \omega_r)\lambda_{dr} + \partial\lambda_{qr}/\partial t \qquad \dots(8)$$
$$V_{ds} = R_S i_{qs} - \omega \lambda_{qs} + \partial\lambda_{ds}/\partial t \qquad \dots (9)$$
$$V_{qr} = R_r i_{dr} - (\omega - \omega_r)\lambda_{qr} + \partial\lambda_{dr}/\partial t \qquad \dots(10)$$
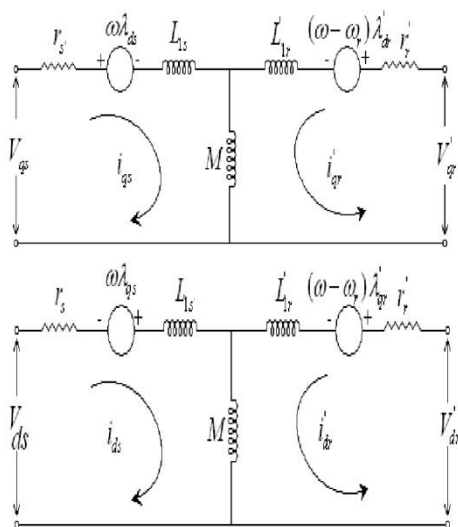$$T_e = 1.5*(P/2)*(i_{ds}* \lambda_{qs} - i_{qs}* \lambda_{ds}) \qquad \dots (11)$$

FIG. 5: Equivalent Induction Machine circuit at dq reference frame.

SIMULINK IMPLEMENATION & 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. 6. The simulation results which validate the DTC principle are shown in Fig. 7 onwards.
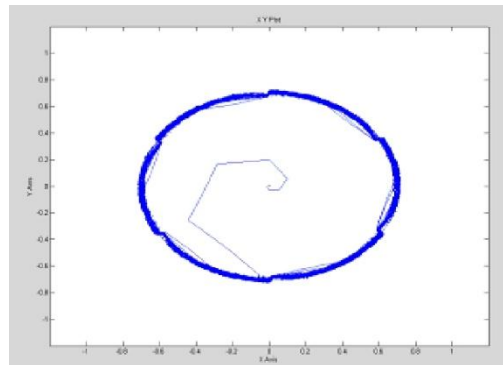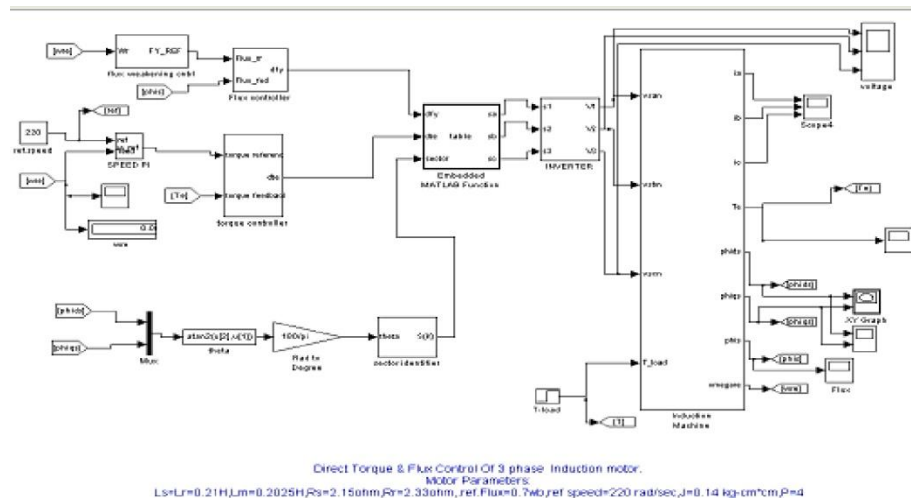

FIG. 6: Stator flux trajectory.
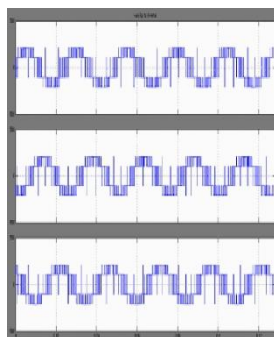

FIG. 7. Simulink Model of DTC scheme.

FIG. 8: Phase voltages of IM   FIG. 10: Torque response for TL=0 NM
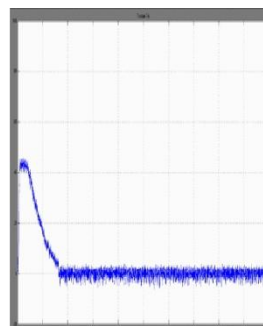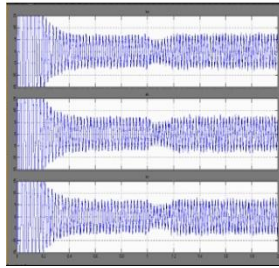
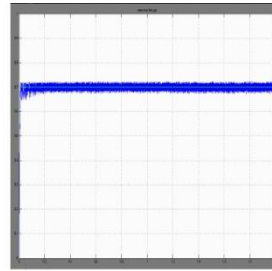FIG. 9: Phase currents of IM   FIG. 11: Stator flux Response (Ref Flux=0.7wb)
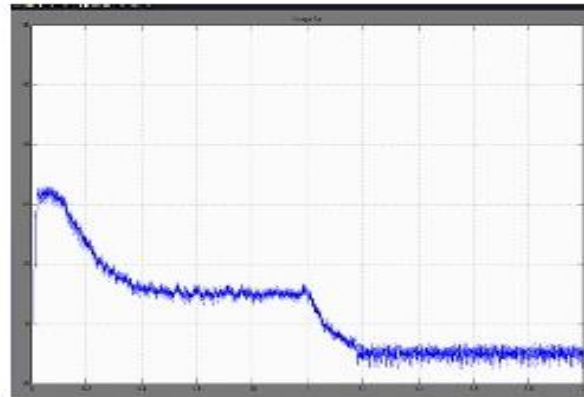

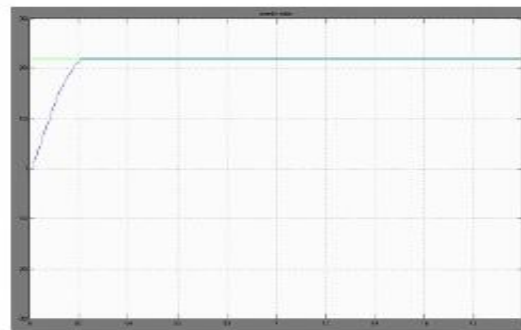FIG. 12: Torque Response for rated Torque reversal

FIG. 13: Speed response in rad/sec (Speed ref = 220 rad/sec).

DISCUSSION & CONCLUSION

Complete simulation of direct torque & flux control has been proposed and demonstrated in this paper. The simulation results agree with the basic principles of the technique. It is clearly seen that 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.

PARAMETERS USED FOR SIMULATION

R_S = 2.15 ohm.
R_r = 2.33 ohm.
L_s = 0.21 Henry.
L_r = 0.2025 Henry.
L_m = 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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