Direct Torque Control Strategy for Induction Motor Drive

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***Abstract*— DTC provide a decoupled control of flux and torque. With DTC method stator flux and torque of induction motor drive are controlled but during estimation process some error occurs in DTC and the switching frequency of inverter are not maintain constant. To control switching frequency SVPWM technique is used. In this method parameter control is achieved by selecting proper inverter switching voltage vector from lookup table. The actual values of controlled variable are estimated from induction motor voltage model. The purpose of this paper is to give a short review of the DTC-SVM techniques and it is devoted basically to the three-phase two-level inverters.**

***Keywords*— Direct torque control (DTC), induction motor (IM) drives, space vector pulse width modulation (SVPWM), voltage source inverter (VSI).**

I. Introduction

In early of 70s, the first vector control method of induction motor was presented by K. Hasse (Indirect Field Oriented Control) and F. Blaschke (Direct Field Oriented Control). The position sensor and current controlled inverter used in FOC because of these estimated values deviate from correct once hence drive performance degrade both in steady state and transient state operation. To overcome this drawback in the middle of 1980's a new vector control strategy for induction motor drives invented by Takahashi and Noguchi called it as a Direct Torque Control (DTC) [16] and by M. Depenbrock as Direct Self Control (DSC). The authors of the new control strategies replaced motor decoupling and linearization via coordinate transformation, like in FOC, by hysteresis controllers. The main advantages of DTC over FOC are requirement of less machine parameter (require only stator resistance), simpler implementation and quicker dynamic torque response. DTC controls the torque and speed of the motor, which is directly based on the electromagnetic state of the motor [16].

To regulate the output voltage, stator current and torque PI controller is used in DTC. A pure integrator has integration drift problem due to dc offset, noise and measurement error present in the back electromotive force. LP filter is used to remove problem due to integration drift [5]. In steady-state condition, the LP filter estimator introduced magnitude and phase errors, thus resulting in an incorrect voltage vector selection. The steady-state drive performance will improve by compensating these errors [7]. But compensation is only valid for steady state condition.

To remove the drift problem and error due to pure integrator, a new integrator with a first order LPF and a high-pass-filter (HPF) in series is proposed [10]. Using LPF and HPF in series offset can be reduced but not removed completely. In order to remove the dc bias caused by the initial value conditions Pre- and Post- High Pass Filtering is used [9]. However, to implement the DTC with this method requires large processor resources and longer execution time for a slower processor.

During estimation process some errors occur in DTC IM drive. These errors are mismatch in the stator resistance, gain errors, offsets and gain unbalance in the transduced variables [12]. The presence of these errors in model parameter transduction degrades the drive performance substantially. By processing inverter dc-link voltage and stator currents controlled variable are estimated such as stator flux and electromagnetic torque [12].

The DTC controls the stator flux and electromagnetic torque directly and independently. Selection of the inverter voltage vectors from switching table provides fast torque and flux control. In DTC, hysteresis controller is used which provide very well on-off operation for inverter semiconductor power devices. Due to torque and stator flux hysteresis band controller ripple are produced in torque and stator current. This DTC scheme comes under classical DTC having several disadvantages. From which the most important is variable switching frequency. The switching frequency varies with the operating speed, load condition and parameters of the induction machine [6]. In order to overcome this problem, a number of methods are there. Recently a new control technique has been developed from classical DTC method called as space vector modulated direct torque control (DTC-SVM) of induction motor drive. Space vector modulation technique is based on representation of three phase voltage as a space vector in a sector of inverter. The main advantages of DTC-SVM technique over classical DTC are constant switching frequency operation. These methods DTC- SVM are the main subject of this project. In SVPWM technique switching losses are less at same carrier frequency as compared to other PWM technique.

In this paper the DTC-SVM scheme is proposed for induction motor drive. DTC-SVM scheme gives good dynamic control of flux and torque. The main advantage of DTC-SVM strategy is to operate in constant switching frequency. Constant switching reduces torque ripple substantially. In constant switching DTC, a switching lookup table is used for optimum selection of voltage vector on corresponding state of inverter. The lookup table design to achieve special requirement of induction motor drive on industry such as low speed, high speed and starting.

II. BASIC PRINCIPLE OF DTC

Basic DTC induction motor drive consist of hysteresis controller, torque and flux estimators, switching lookup table and voltage source inverter.

The basic principle of DTC is the direct selection of a space vector using look up table and corresponding control signals of voltage source inverter, in order to control instantaneously the electromagnetic torque and stator flux magnitude [3]. The main drawback associated with the conventional DTC was the high torque, flux ripples and also variable switching frequency of the devices. This drawback was rectified with the using of space vector modulation (SVM) technique.

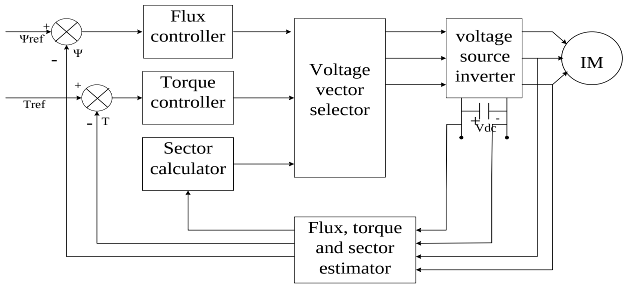

Fig. 1. Block diagram of DTC.

Methods for performance improvement of classical DTC can be classified in two categories as:

- DTC with modified lookup table methods.
- DTC with constant switching frequency using SVPWM.

The dynamic performance of the induction motor drives improves in high rate by using SVPWM technique compared to the other conventional speed control technique of induction motor drives. The SVPWM method is an advanced PWM method and best among other PWM techniques for variable frequency drive application. SVPWM technique provides space vector with lower harmonics and high modulation index compare to other modulation technique.

III. DTC BACKGROUND

A. *Mathematical model of Induction motor*

Stator and rotor voltage equation of induction motor is

$$Vs = \frac{d\Psi s}{dt} + Rs.Is$$

$$0 = \frac{d\Psi s}{dt} - j\omega.\Psi r + Rr.ir$$

This mathematical description is based on space vector notation.

Instantaneous stator phase voltage values can be written:

$$Va = IaRa + \frac{d\Psi a}{dt}$$

$$Vb = IbRb + \frac{d\Psi b}{dt}$$

$$Vc = IcRc + \frac{d\Psi c}{dt}$$

The space vector method is generally used to describe the model of the induction motor. A three phase quantities of motor such as voltage, current or flux linkage can be replaced by one resulting space vector of voltage, current or flux linkage.

For given a set of three-phase voltages, a space vector can be defined by

$$\overrightarrow{V(t)} = \frac{2}{3}[Va(t)e^{j0} + Vb(t)\ e^{j\frac{2\pi}{3}} + Vc(t)e^{j\frac{4\pi}{3}}]$$

Where Va(t), Vb(t), and Vc(t) are three sinusoidal voltages of the same amplitude and frequency but with 120^0 phase shifts.

B. *Voltage Source Inverter (VSI)*

A 3 phase two level voltage source inverter is used in direct torque control method. VSI consist of dc link voltage and six switches. The states of lower switches i.e. S1, S3, S5 are opposite of the upper one i.e.S2, S4, S6 to prevent short circuit of the supply. The possible inverter voltage vector configuration is 2^3 =8. Out of 8 voltage (V0 to V7) vector six are active vector (V1 to V6) and two are zero vector (V0,V7). The VSI form the voltage vectors which are commanded by the switching table.

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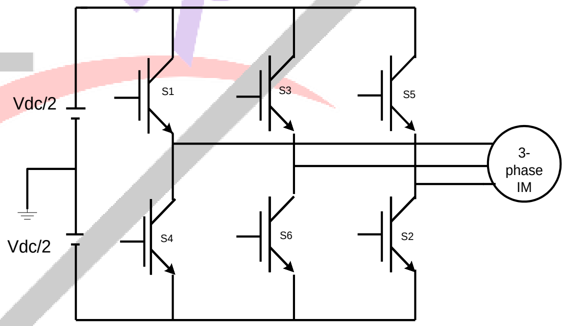

Fig.2. Three phase voltage source inverter.

Table 1. The standard 8 voltage vectors and the logic states.

	V0	V1	V2	V3	V4	V5	V6	V7
A	0	1	1	0	0	0	1	1
B	0	0	1	1	1	0	0	1
C	0	0	0	0	1	1	1	1

C. *Torque hysteresis controller*

Torque of induction motor in terms of stator and rotor flux linkages can be written as

$$Te = \frac{3}{2}\frac{Lm}{\sigma LsLr}\psi s\ \psi r \sin \delta sr$$

In DTC the torque of the motor is controlled within its hysteresis band. Induction motor operates motoring mode as well as braking mode. For such operation three level digital hysteresis comparator is used in DTC induction motor drive [13]. The estimated torque is subtracted from the reference torque to obtain the torque error which is then fed to hysteresis comparator. Hysteresis comparator will produce torque error status in three level digital output i.e. 1, 0, and -1.

H_T = 1 for $E_{Te} > +HB_{Te}$
0 for $HB_{Te} < E_{Te} < +HB_{Te}$
1 for $E_{Te\_} < -HB_{Te}$

Where, H_T - Torque error status
E_{Te} - Torque error
HB_{Te} -Total hysteresis band width of the torque loop controller.

D. Flux hysteresis controller

In DTC stator flux of the induction motor is controlled on the hysteresis band. The hysteresis band width for stator flux vector is taken as $2HB_\Psi$. With the help of hysteresis comparator stator flux vector is rotate within flux hysteresis band. Two level hysteresis controller is used to control the stator flux vector rotation within hysteresis band. The estimated stator flux is subtracted from the corresponding reference flux values to obtain the flux error. The flux error is then fed to the hysteresis comparator to produce flux error status which either 1 or 0.
The flux loop controller has two levers of digital output according to the following relations [13].

H_Ψ = 1 for $E_\Psi > +HB_\Psi$
0 for $E_\Psi < -HB_\Psi$

Where, H_Ψ - flux error status
E_Ψ - flux error
HB_Ψ - The total hysteresis band width of the flux loop controller.

E. Switching Selection

The demanded values of stator flux and torque obtained from both hysteresis controllers is used for calculation of voltage vector rotation in particular sector of plane. The optimum selection of the switching voltage vectors in all six sectors of the stator flux plane can be tabulated using voltage vector selection table given by Table 2. The table is used to select the voltage vectors in particular sector for clockwise or anticlockwise selection of stator flux orientation depending on flux error, torque error.

Table 2. Lookup table of DTC scheme.

$d\Psi_s$	dTe	Θ1	Θ2	Θ3	Θ4	Θ5	Θ6
1	1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
-1	1	V3	V4	V5	V6	V2	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

F. Direct Flux Control

The stator voltage equation of induction motor can be written as

$$\frac{d\psi s}{dt} = Vs - RsIs$$

By rearranging equation the stator flux in stationary frame can be written as,

$$\Psi s = \int Vs - i_s.\ R_s$$

The stator resistance voltage drop is neglected to fixed the stator flux vector direction along the selected voltage vector. Over a small period of time, stator flux can be written as

$$\Delta\Psi s = Vs.\ \Delta t$$

Which means that stator flux Ψs , can be change by applying stator voltage vector Vs for a time interval Δt [11]. As time increments stator flux vector changes incrementally. The stator flux vector orientation corresponding to each of the six inverter voltage vector is shown in fig.3. Stator flux vector is integral of stator voltage space vector. To increase the flux linkage space vector the voltage vector must be directed out from the centre of rotor. To reduce stator flux linkage space vector the voltage vector must be directed towards the centre of rotor. To control the stator flux vector, the magnitude and direction of rotation of the stator flux must be known. The stator flux plane is divided into minimum six sectors and angle between them is π/3rad.

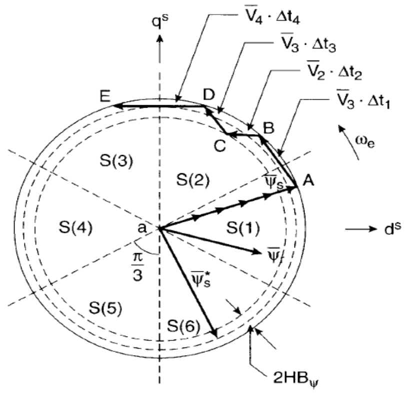

Fig.3. Trajectory of stator flux vector in DTC [11].

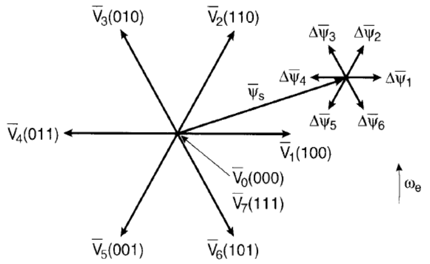

Fig.4. Inverter voltage vector and corresponding stator flux variation in time Δt [11].

IV. DISCUSSION OF RESULTS

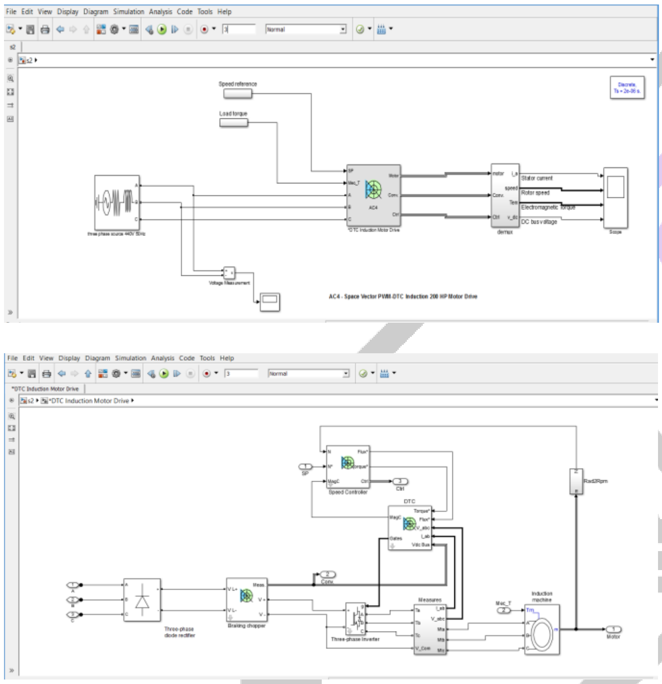

Fig 5- Simulink model of space vector pulse width modulated DTC induction motor drive.

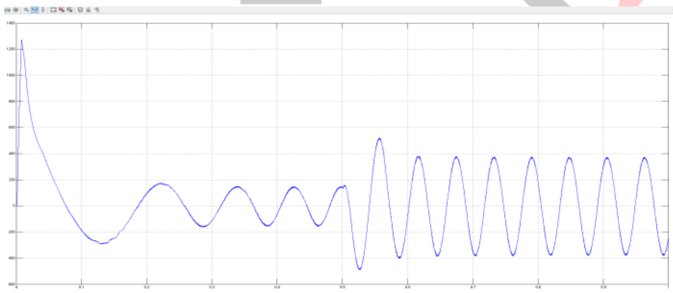

Fig.6. d-axis stator current waveform.

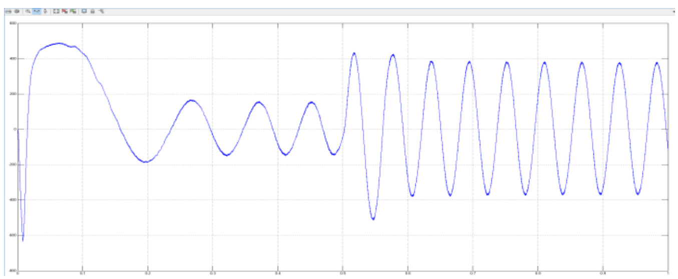

Fig.7. q-axis stator current waveform.

From above fig.6 and fig.7 it is shown that decoupled control is possible in DTC induction motor drive.

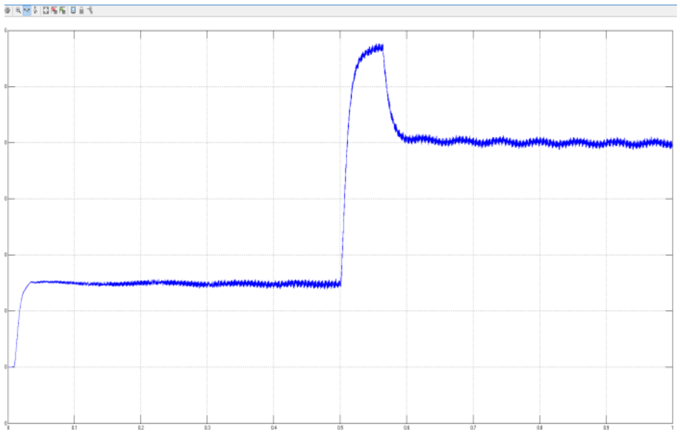

Fig.8. Waveform of estimated torque.

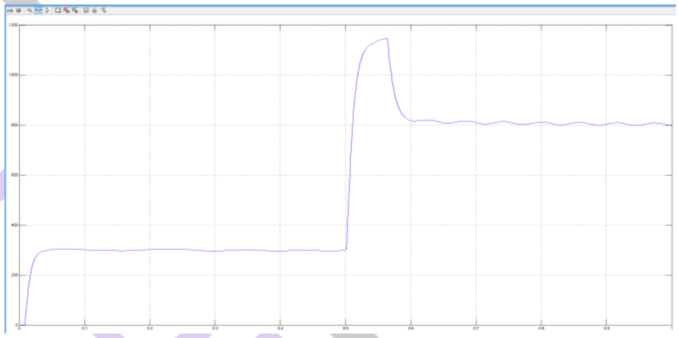

Fig.9. Waveform of reference torque

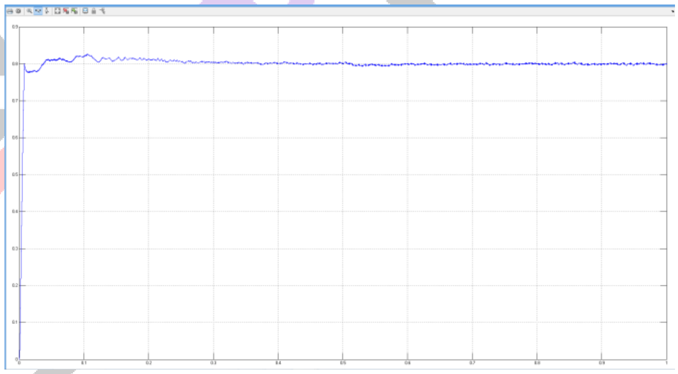

Fig.10. Waveform of estimated flux.

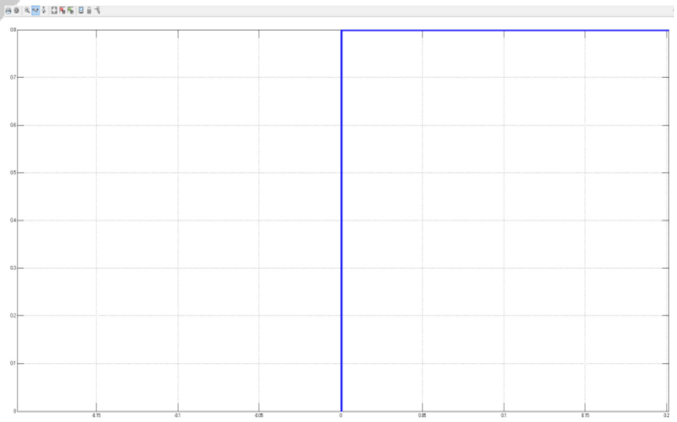

Fig.11. Waveform of reference flux.

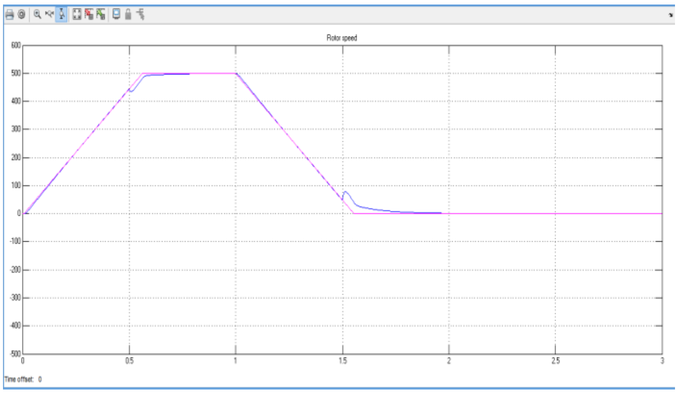

Fig.12. Rotor speed waveform.

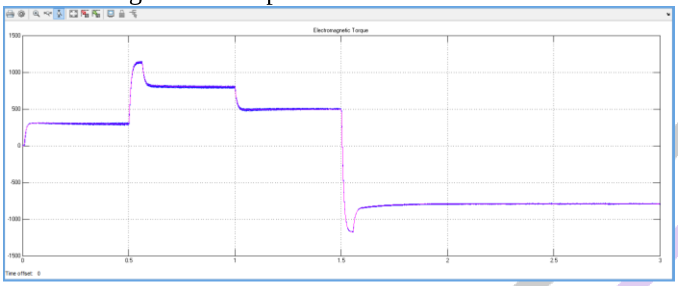

Fig 13. waveform of electromagnetic torque.

Figure 12 and Figure 13 shows the electromagnetic torque and the rotor speed of the machine. This shows that the DTC achieved high dynamic performance in speed response to changes in demand torque. However, there is some performance degradation with torque overshoot because of the hysteresis controllers used in DTC model. Initially torque has high initial value in the acceleration zone and it increase as load torque increase after sometime it starts decreasing and remain constant in the deceleration zone. Fig.9 shows the electromagnetic torque curve, at first speed increases and then it comes to steady state so that flux is maintained constant to control the torque.

V. CONCLUSION

This paper has reviewed DTC strategies for SVPWM inverter- fed IM motor drives. DTC-SVM scheme maintain Constant-switching-frequency and it reduced torque and flux pulsations.

VI. FUTURE SCOPE

To improve drive performance by removing error due to integration drift caused by initial value error and gain error caused by inaccuracies in circuitry used in sensing, scaling and filtering dc link voltage and stator current.

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