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Simulation of Direct Torque Control of Induction motor using Space Vector Modulation Methodology

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Abstract: *This paper presents simulation of Direct Torque Control (DTC) of Induction Motor using Space Vector Modulation (SVM). Direct Torque Control is a control strategy used for high performance torque control of Induction Motor. This SVM based DTC technique reduces torque ripple and improves torque response. The performance is explained using simulation in MATLAB environment. Result of the simulation done in the paper shows improvement in flux and torque. These results verifies the merits of DTC- SVM over conventional Direct Torque Control technique.*

Keywords: *About DTC, SVM, Stator flux, Flux error, Torque error.*

I. List Of Symbols

IM	Induction Motor
DTC	Direct Torque Control
SVM	Space Vector Modulation
Hz	Hertz
kW	kilo-Watt
VSI	Voltage Source Inverter
P	Number of pair poles
T_e	Electromagnetic Torque
R	Resistance
L	Inductance
J	Inertia
T	Torque
Ω	Ohm
ω_s	Stator Angular Speed
ω_r	Rotor Angular Speed
Ψ	Flux Linkage
α	Angle between stator flux & Rotor flux
H	Hysteresis Band
IGBT	Insulated Gate Bipolar Transistor

II. Introduction

Direct Torque control (DTC) for induction motor was introduced about thirty years ago by Japanese and German researchers Takahashi and Noguchi is considered as an alternative to the field oriented control (FOC) or vector control techniques. These two control strategies are different on the operation principle but their objectives are the same.

Direct torque control is receiving wide spread attention in the recent literature [3], [4]. It minimizes the use of machine parameters [5], [6]. Direct Torque Control (DTC) is one of the excellent control strategies of torque control/ speed control in induction machine. This uses the hysteresis band to control the flux and torque of the machine directly. When the stator flux falls outside the hysteresis band, the inverter switching stator changes so that the flux takes an optimal path toward the desired value [5], [6]. The name direct torque control is derived from the fact that on the basis of the errors between the reference and the estimated values of torque and flux it directly controls the inverter states in order to reduce the torque and flux errors within the prefixed band limits [7], [8].

This paper describes simple & effective MATLAB simulation of direct torque control of Induction Motor using Space Vector Modulation. The induction motor model, principal of space vector modulation technique, advantages of DTC SVM are explained. The results of this simulation is explained at the end

III. INDUCTION MOTOR MODEL

The following equations written in terms of space voltage vector in a stationary reference frame describe the dynamic behavior of an induction motor

3.1 Voltage Equation

$\vec{V_S} = R_S\vec{I_S} + \frac{d}{dt}\vec{\psi_S}$ …………………………… (1)

$\vec{V_r} = 0 = R_r\vec{I_r} + \frac{d}{dt}\vec{\psi_r} - j\omega_r\vec{\psi_r}$ …………….. (2)

Where

$\vec{V_S} = [V_{ds} \quad V_{qs}]^T$ = Space vector of stator voltage,

$\vec{\psi_S} = [\psi_{ds} \quad \psi_{qs}]^T$ = Stator Flux Vector

$\vec{\psi_r} = [\psi_{dr} \quad \psi_{qr}]^T$ = Rotor Flux Vector

$\vec{I_S} = [I_{ds} \quad I_{qs}]^T$ = Stator Current Vector

$\vec{I_r} = [I_{dr} \quad I_{qr}]^T$ = Rotor Current Vectors

(R_sR_r) and (L_sL_r) are respectively the stator & rotor resistance and inductance , L_m is mutual inductance, ω_r is motor angular speed in electrical rad/sec.

3.2 Torque Equations

The torque equation for induction machine can be represented by in vector form as,

$T_e = \frac{3}{2}\frac{P}{2}\overline{\psi_s}\,\overline{I_s}$ ……………………………... (3)

In this equation, $\overline{I_s}$ is to be replaced by rotor flux $\overline{\lambda_r}$. In this complex form, $\overline{\lambda_s}$ and $\overline{\lambda_r}$ can be expressed as functions of currents as,

$\vec{\psi_s} = L_S\vec{I_S} + L_m\vec{I_r}$ …………………………...(4)

$\vec{\psi_r} = L_r\vec{I_r} + L_m\vec{I_s}$ ………………. …………(5)

Eliminating $\vec{I_r}$ from equation (5) we get,

$\vec{\psi_s} = L_m\frac{L_m}{L_r}\vec{\psi_r} + L'_s\vec{I_s}$ ………………………(6)

Where,

$L'_s = L_sL_r - \overline{L_m^2}$

The corresponding equation of $\vec{I_s}$ is

$\vec{I_s} = \frac{1}{L'_s}\vec{\psi_s} + \frac{L_m}{L_rL'_s}\vec{\psi_r}$ …………………..…….(7)

Substituting equation (7) in (3) and simplifying yields

$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_rL'_s}\overline{\vec{\psi_r}\vec{\psi_s}}$ ……………………...…..(8)

That is magnitude of torque is,

$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_rL'_s}\left|\vec{\psi_r}\right|\left|\vec{\psi_s}\right|\sin\propto$ …………………(9)

IV. DIRECT TORQUE CONTROL

DTC provides very fast response with simple control structure and hence this technique is gaining popularity in industries. In DTC, stator flux and torque are directly controlled by selecting the appropriate inverter state. The stator currents and voltages are indirectly controlled hence no current feedback loops are required. Stator fluxes and stator currents enable high dynamic performance even at standstill. The generic DTC scheme for a Voltage source PWM inverter-fed IM drive is shown in Fig.1. The stator flux controller imposes the time duration of the active voltage vectors, which move the stator flux along the reference trajectory, and the torque controller determinates the duration of the zero voltage vectors which keeps the motor torque in the predefined hysteresis tolerance band. At every sampling time the voltage vector selection block chooses the inverter switching state (SA, SB, SC) which reduces the instantaneous flux and torque errors

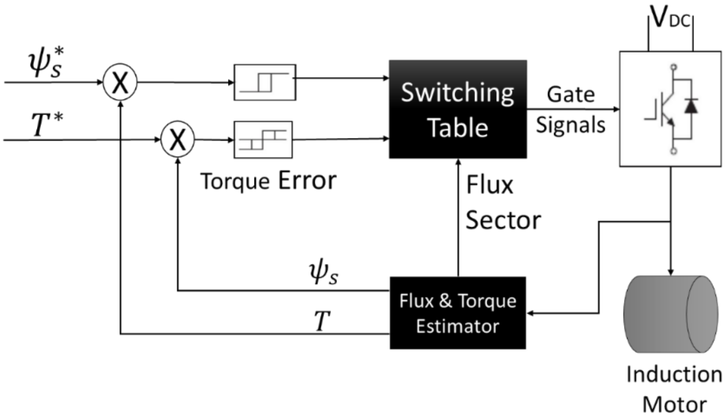


Fig. 1 Basic DTC Scheme

V. DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING SPACE VECTOR MODULATION

Direct Torque control of Induction Motor using Space Vector Modulation is shown in fig2. As shown in this scheme the stator voltage & current parameters are used for calculation or estimation of actual flux & torque. Estimated flux & torque are the compared with reference flux & torque values. Error obtained after comparison is given to the flux & torque controller. The limits of these hysteresis controllers are explained in equations below. Suitable vector is selected from the lookup table as per the values of flux error, torque error & flux sector number. The vector selected is given to the inverter and the converter output is applied to the motor.

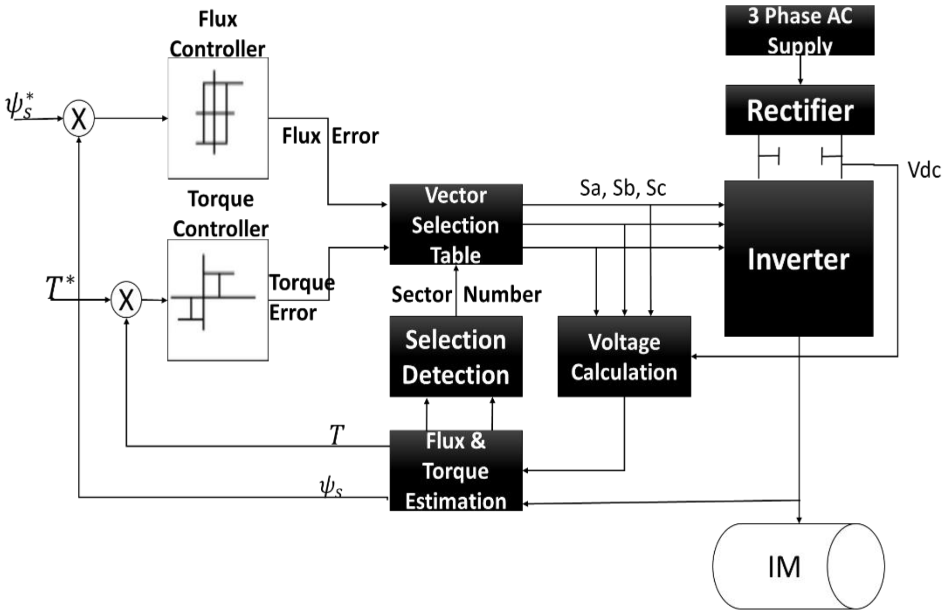


Fig. 2 DTC SVM Scheme

The basic idea of the switching table DTC SVM concept is shown in Fig. 2. The command stator flux Ψ_s^*, and torque T^* values are compared with the actual Ψ_s and T_e values in hysteresis flux and torque controllers, respectively. The flux controller is a two-level comparator while the torque controller is a three level comparator. The digitized output signals of the flux controller are defined as in equation (7) and (8)

$$\psi_{error} = 1, for\ \psi_s < \psi_s^* - H_\psi \text{............(7)}$$

$$\psi_{error} = -1, for\ \psi_s < \psi_s^* + H_\psi \text{............(8)}$$

And those of the torque controller as in equations λλ

$$T_{error} = 1, for\ T < T^* - H_{\psi}$$ ……………(9)

$$T_{error} = 0, for\ T = T^*$$ ………………..(10)

$$T_{error} = -1, for\ T < T^* + H_{\psi}$$ ……………….(11)

where 2HΨ is the flux tolerance band and 2Hm is the torque tolerance band. The digitized variables Ψ, Te and the stator flux section (sector) N, obtained from the angular position

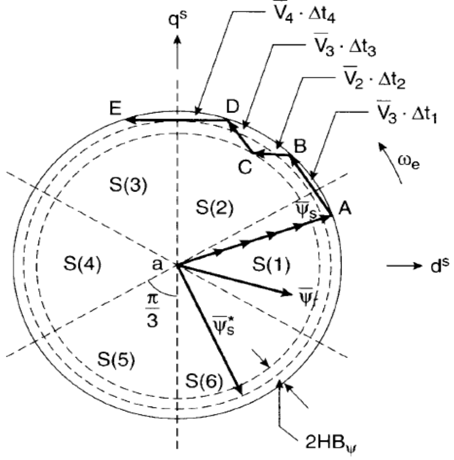


Fig. 3. Trajectory of stator flux vector in DTC Control

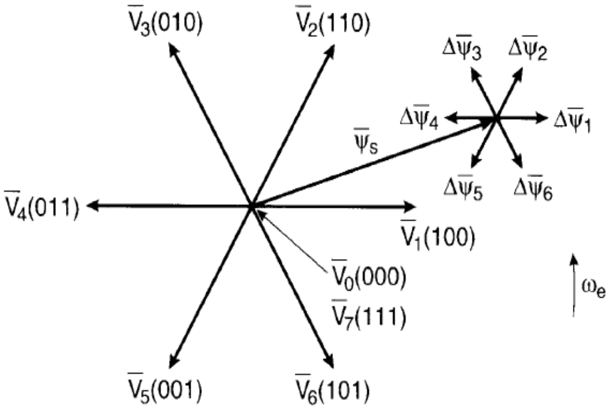


Fig.4. Inverter Voltage vectors and corresponding stator flux variation in time Δt

The angular position flux vector can be calculated using following angle ranges as

- 30< α (1) < 30
30< α (2) < 90
90< α (3) < 150
150< α (4) < 210
210< α (5) < 270
270< α (6) < 330

On the basis of torque and flux hysteresis status and the stator flux switching sector, which is denoted by α, DTC algorithm selects the inverter voltage vector from the table.

The outputs of the switching table are the settings for the switching devices of the inverter. Fig.2 shows the relation of inverter voltage vector and stator flux switching sectors.

Six active switching vectors V1, V2, V3, V4, V5, V6 and two zero switching vectors V0 and V7 determine the switching sequence of the inverter. Depending on inverter switching pulses, PWM is achieved and hence stator voltages and currents are controlled [3]. Therefore to obtain a good dynamic performance, an appropriate inverter voltage vectors Vi (i=1 to 6) has to be selected.

Ψ error	**T error**	**α (1)**	**α (2)**	**α (3)**	**α (4)**	**α (5)**	**α (6)**
		Sec 1	**Sec 2**	**Sec 3**	**Sec 4**	**Sec 5**	**Sec 6**
1	**1**	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
0	**1**	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

VI. SIMULATION OF DIRECT TORQUE CONTROL OF INDUCTION MOTOR

6.1 FLUX & TORQUE ESTIMATOR

This block is used to calculate values of flux and torque.

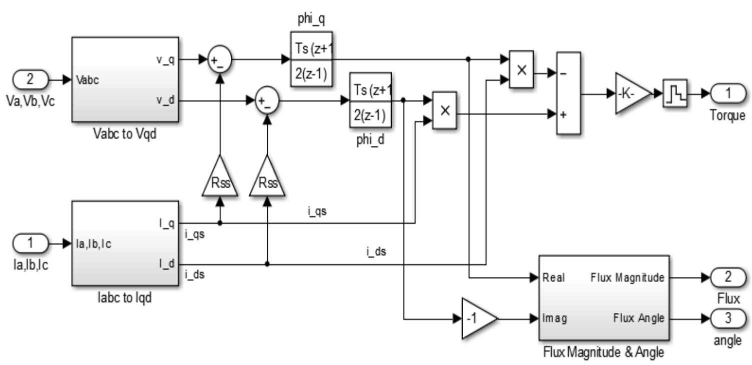


Fig. 5. Flux & Torque estimator

6.2 SPEED CONTROLLER

In this block reference speed & actual speed are calculated. By calculating actual & reference speed, error is given to the PI controller. The PI controller is tuned by setting proper values for proportional and integral constant and these values are found to be K_P=1 and K_i=80. Output of this controller acts as a reference torque.

6.3 FLUX AND TORQUE HYSTERESIS CONTROLLER

After comparison of reference flux & torque with actual flux & torque, errors are calculated in this block. In flux hysteresis controller, two level hysteresis controller is used. The switch ON & OFF limits are 0.02 & -0.02. For calculating torque error, three level hysteresis controller is used.. Outputs of this block are flux & torque error. These errors are given to switching table.

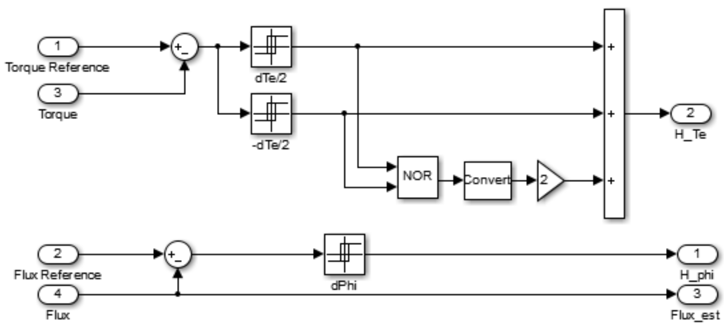


Fig. 6 Flux & Torque Hysteresis Controller

6.4 SWITCHING TABLE

After receiving the error signals from hysteresis controller, suitable voltage vectors from V_0 to V_7 are selected from the look up table shown in section 4. The output of this is given to IGBT inverter. But as IGBT inverter required six pulses such that in each arm both IGBT's should get input inverted from other hence we have inverted the voltage vectors and all six pulses are given to inverter. The delay of 10µs is added between these pulses.

VII. SIMULATION & RESULT

The following model is developed in MATLAB using above mentioned blocks. This model is run for typical conditions of reference speed & applied torque. The flux produced along with reference flux is shown. Switching states of all the IGBT during running are shown. The parameters 3 phase induction motor is shown in following

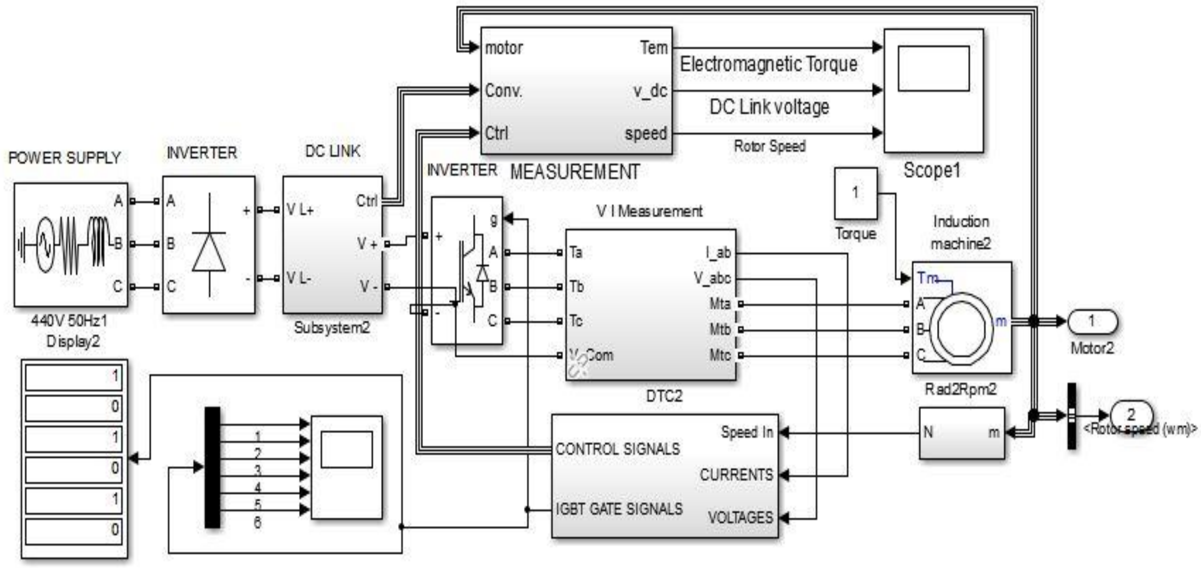
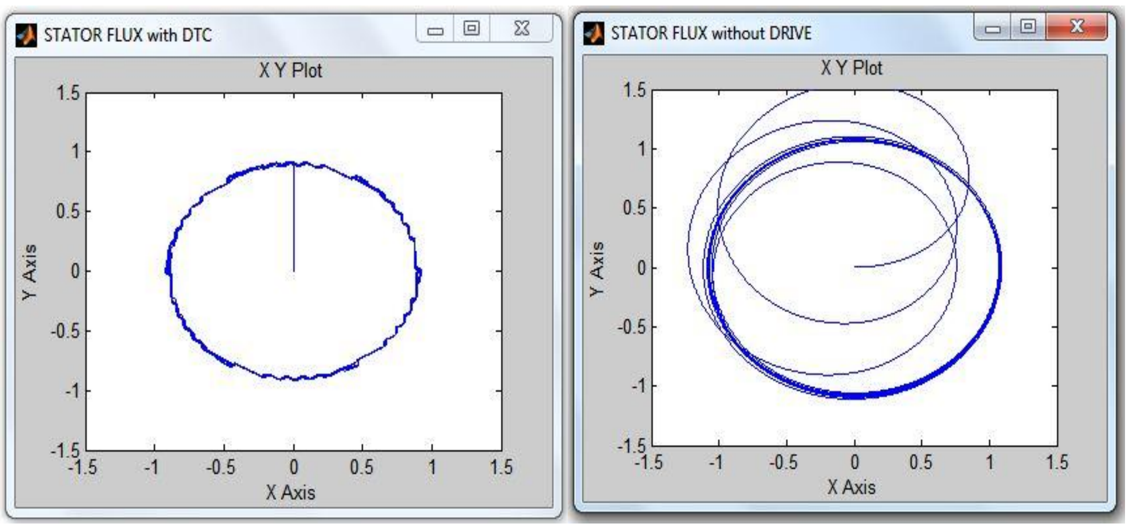


Fig.7. Simulation of DTC -SVM

The same induction motor is also run without any type of torque control strategy. The stator flux pattern is observed and studied. The stator flux with DTC is shown in fig. 8 (a). Another stator flux without any type of control strategy is shown in fig. 8 (b).



(a) (b)

Fig. 8 (a) Stator Flux with DTC Drive (b) Stator Flux without DTC Drive

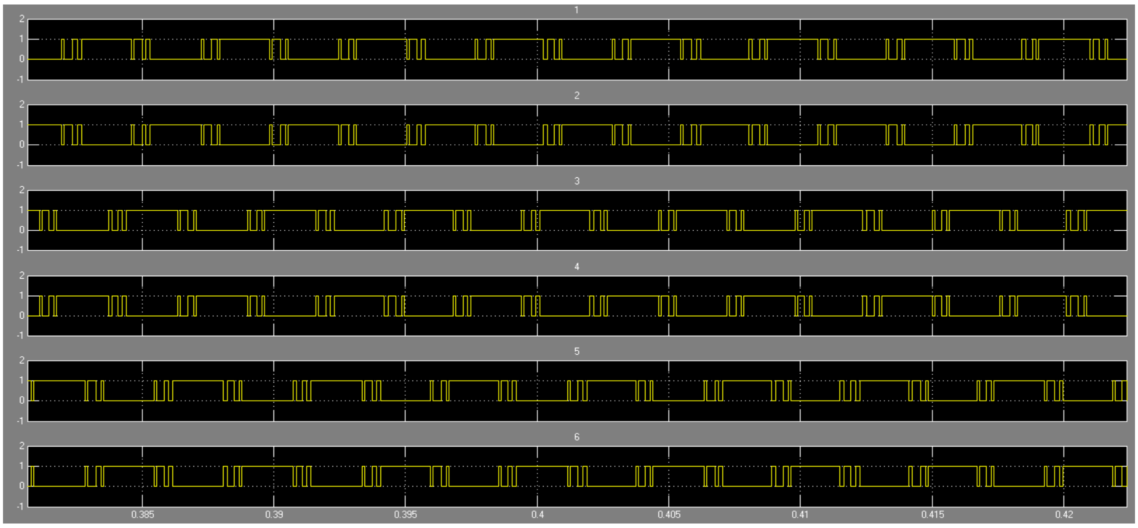


Fig. 9. Switching States of IGBT

The DC Link Voltage is shown below. It is observed that DC link voltage is increase to high value before settling at 580V. The variation is shown in fig.10.

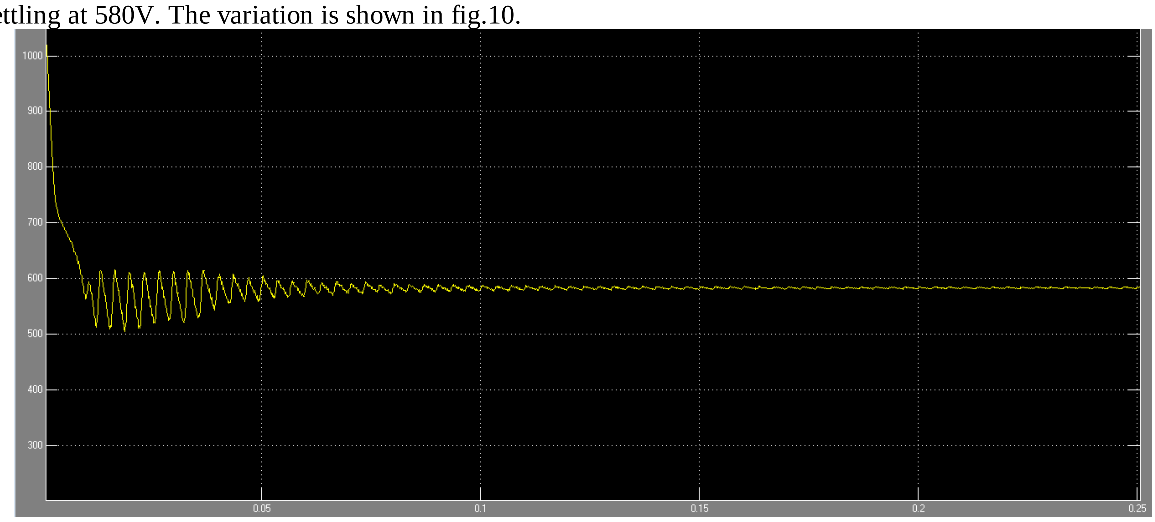


Fig. 10 DC Link Voltage

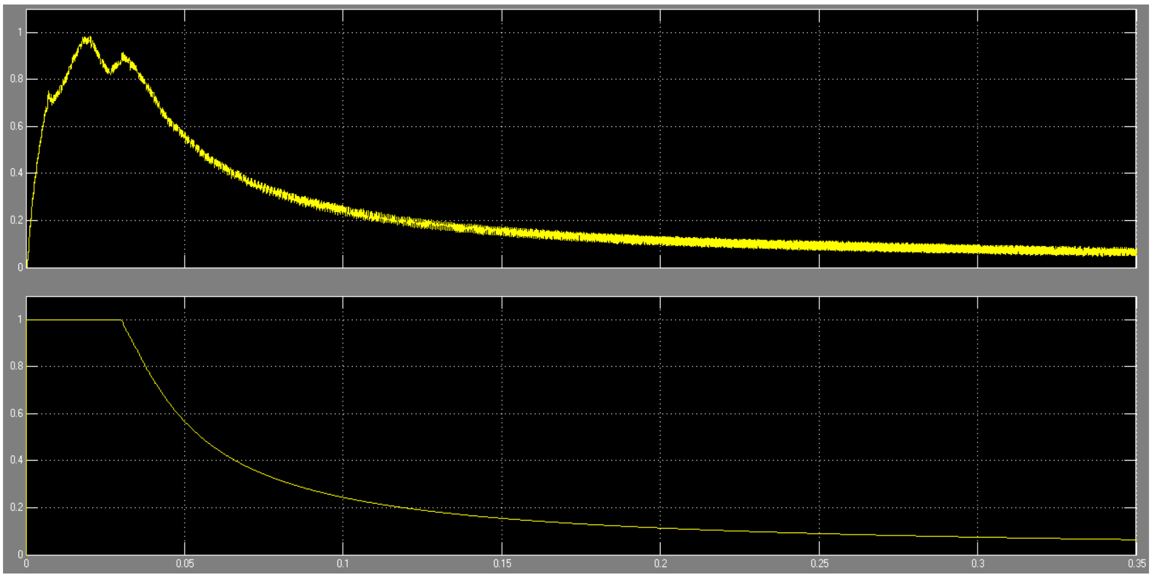


Fig.11 Actual & Reference Stator Flux

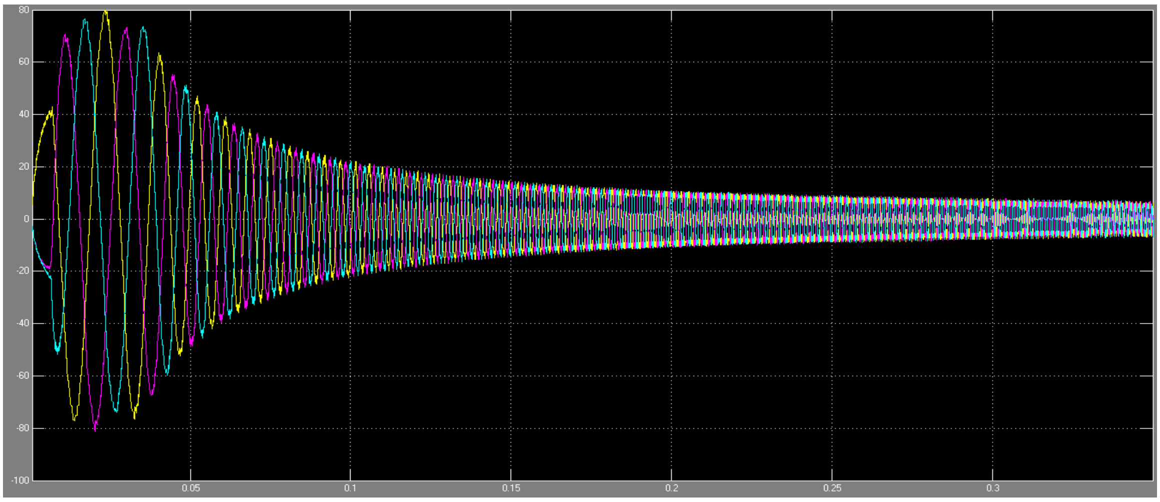


Fig. 12 Stator Currents

VIII. CONCLUSION

The DTC scheme is analyzed using MATLAB Simulink environment. It is observed that this open loop torque control of Induction motor develops uniform torque with reduction in torque ripples & improvement in torque response. This type of control requires estimation of torque and flux form the stator parameters which is explained in this paper. Implementation of DTC has shown uniform stator flux. The simulation of Induction motor without DTC with comparison of non-uniform flux produced in absence of DTC. Thus the results verifies the merits of the DTC SVM system.

IX. Future Work

Implementation of DTC scheme using high power switching devices like IGBT & IGCT & compare the performance. Implementation of DTC with modified control strategy of 12 voltage sectors can also be done.

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