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Modeling and Simulation of Direct Torque Control of Induction Motor Drive

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Abstract— The main focus of this paper is towards the analysis of Direct Torque Control (DTC) scheme with Space Vector Modulation (SVM) technique. Dynamic performance of the induction motor is improved by the DTC-SVM technique. Both motor and inverter are controlled in most efficient way by DTC. The fast control of torque and flux in Induction Motor (IM) without complexity is the feature of DTC. The selection of voltage vector for the desired resultant voltage vector is described and the IM is simulated for both DTC and without DTC system.

Index Terms— Direct Torque Control (DTC), Induction Motor Modeling, Space Vector Pulse Width Modulation (SVPWM)

1 INTRODUCTION

A wide range of speed and power is covered by squirrel cage rotor type induction motor and is generally used in many industries. Use of vector control allows the control of induction motor same as that of separately excited dc motor. Two methods of Induction Motor Drive (IMD) control are scalar and vector control method. The angular speed of current, flux linkage and voltage in space vectors are controlled by scalar control operating in steady state. Instantaneous positions of current, voltage and flux linkage of space vector are controlled using vector control [2].
AC motors are used in most of the electrical drive due to development of low cost converters with progress taken place in power electronics and other advantages of ac motors over dc motors like absence of commutator, less maintenance cost, volume, weight making motor inexpensive. Induction motors performs better in high torque and speed and are robust. AC motor's high level of speed control can be achieved with the help of the trans-vector theory but for a wide range of applications its controllers are too complex hence Direct Torque Control (DTC) is used as alternative. In AC motor drives DTC become more popular technology. DTC is simple in structure and has good dynamic behavior giving high performance and efficiency [3].
High torque and flux ripples, variable switching frequency, problem during starting and low speed operating conditions and current and flux distortion caused by stator flux vector changing with the sector position are the drawbacks of conventional DTC.

2 INDUCTION MOTOR MODEL

The stator and rotor voltage of induction motor are given as

$$V_s = \frac{d\psi_s}{dt} + R_s i_s$$
$$0 = \frac{d\psi_r}{dt} - j\omega.\psi_r + R_r i_r$$

Rotor voltage has zero magnitude as rotor windings are short circuited. Modeling of induction motor in stator co-ordinates by its voltage equations is given as

$$V_s = \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$
$$\psi_s = \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix}$$
$$i_s = \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}$$
$$\psi_r = \begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix}$$
$$i_r = \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix}$$

The above equations give stator voltage, stator flux linkage, stator current, rotor flux linkage and rotor current respectively.
Where,
ω_r – Rotor speed in elect.rad/sec
R_r – Rotor resistance
R_s – Stator resistance
The stator and rotor flux linkages in the form of stator and rotor currents are as

$$\psi_s = L_s i_s + L_m i_r$$
$$\psi_r = L_r i_r + L_m i_s$$

Where,
L_s – Stator self inductance
L_r – Rotor self inductance
L_m – Mutual inductance
Equations of Induction Motor in d-q axis reference frame are given as

$$V_{ds} = r_s i_{ds} + p\psi_{ds}$$
$$V_{qs} = r_s i_{qs} + p\psi_{qs}$$
$$V'_{dr} = r'_r i'_{dr} + p\psi'_{dr} + \omega_r \psi'_{qr}$$
$$V'_{qr} = r'_r i'_{qr} + p\psi'_{qr} - \omega_r \psi'_{dr}$$

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Zero sequence components do not take part in the production of torque hence can be avoided. Flux linkages are given as

$$\psi_{ds} = L_s i_{ds} + L_m i'_{dr}$$
$$\psi_{qs} = L_s i_{qs} + L_m i'_{qr}$$
$$\psi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$
$$\psi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$$

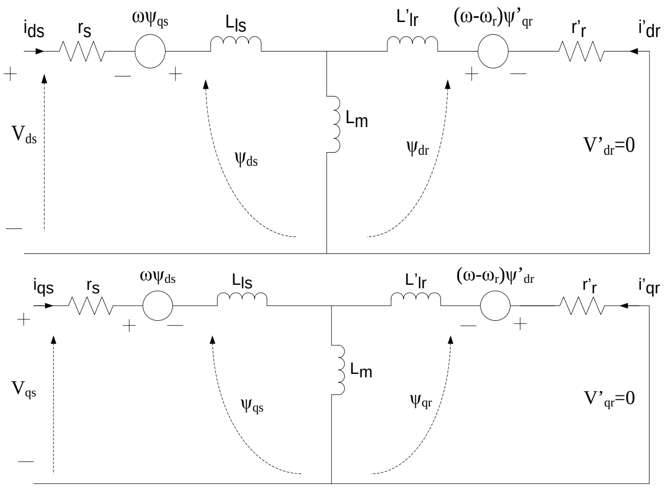

Fig.1 d-q Equivalent Circuit of IM.

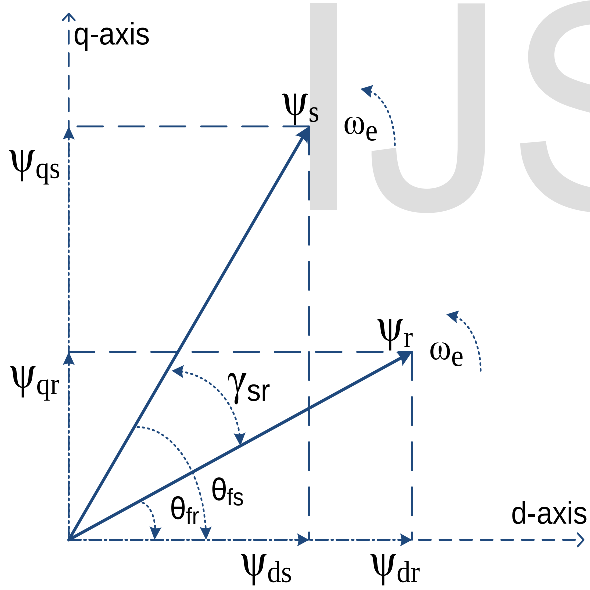

Fig.2 Vector Diagram for IM.

In three phase induction motor, the electromagnetic torque is given as

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi_{ds}.i_{qs} - \psi_{qs}.i_{ds}\right)$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}\left(\psi_{qs}.\psi_{dr} - \psi_{ds}.\psi_{qr}\right)$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}\left|\psi_s\right|\left|\psi_r\right| \sin\gamma_{sr}$$

Where,
σ – Leakage factor
γ_{sr} – angle between stator and rotor flux and is similar to torque.
By changing the angle between the two fluxes it is able to control the torque. The motor may saturate if the value of the flux should not kept constant and motor can't deliver rated power. Hence γ_{sr} controlled to control the torque.

3 Direct Torque Control

DTC has simple control structure, robustness, fast dynamic response etc. By selecting the optimum inverter voltage vector the control of the stator flux linkage and electromagnetic torque has been done in DTC. The switching look-up table provides fast torque response, low harmonic losses and low inverter switching frequency. The direct torque control (DTC) scheme is represented in figure.

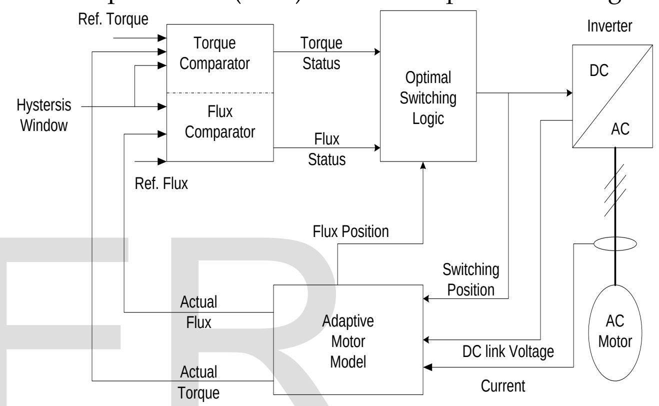

Fig.3 Basic DTC Scheme.

It consists of torque comparator and flux comparator block along with optimal switching logic. The main part of the DTC is accurate adaptive motor model. The actual torque, stator flux and actual aped are estimated by adaptive motor model. The actual values are compared with the reference values of stator flux and torque which gives error values. The two level and three level hysteresis blocks are fed with stator flux and torque errors respectively which are then fed to the optimal switching logic block and then switching logic is given to the inverter. The main objective of the DTC technique is to control the flux linkage directly.

4 Principle of DTC

Traditionally field oriented control (FOC) technique has been used for the control of Induction Motor torque which involve transformation of stator currents into d-q reference frame aligned. Both torque and flux errors are determined by the instantaneous value of flux and torque calculated from the terminals of induction motor. The selection of proper voltage vectors to drive induction motor with the help of switching look-up table is based on these errors. The estimation of flux is based on the stator voltage vector (stator resistance neglected) and is given as

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$$\bar{\psi}_s = \int_0^{\Delta t} (\bar{V}_s - \bar{\iota}_s R_s) = \bar{V}_s \Delta t$$

The output voltage is regulated using PI controller for achieving desired stator current and therefore torque. The transient response of the torque controller is limited by PI controller. To achieve a desired output torque in DTC an effective induction motor has to be used. The values of stator flux and output torque can be achieved by current and voltage measurements with the help of induction motor within fixed time. This desired voltage is then synthesized by Space Vector Modulation (SVM).

5 DTC WITH SPACE VECTOR PULSE WIDTH MODULATION

Space Vector Pulse Width Modulation (SVPWM) is one of the best and advanced techniques used in variable frequency drive. The main objective of this technique is to have variable output with minimum harmonics and maximum fundamental component. It gives minimum total harmonic distortion (THD) and higher voltage which is further fed to motor. The transformation of the three phases to their equivalent two phase quantities has been done using this modulation technique in stationary or synchronously rotating frame. The reference vector magnitude is derived from these two components which modulates the inverter output. The three phase sinusoidal voltage component of stationary frame is given as

$$V_a = V_m \sin \omega t$$
$$V_b = V_m \sin(\omega t - \frac{2\pi}{3})$$
$$V_c = V_m \sin(\omega t + \frac{2\pi}{3})$$

A rotating flux is produced in the air-gap of the AC machine when this three phase voltage is applied. By Clark's transformation, the magnitude and angle of the rotating vector is found out.

$$f_{dq0} = k_s f_{abc}$$

Where,

$$f_{dq0} = [f_d \quad f_q \quad f_0]^T$$

$$f_{abc} = [f_a \quad f_b \quad f_c]^T$$

$$k_s = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

In SVPWM we obtain eight vectors out of which two are zero vectors and six are non-zero vectors. Zero vectors supplies zero voltage to the load. Two adjacent non-zero vectors are 60^0 apart forming the shape of regular hexagon. By using these eight different switching patterns the reference voltage vector is achieved. In 180^o mode of operation, three switches should be on at the same time but with the condition that two switches of the same leg should not be turned on. From Fig.4 if the initial flux is ψ_s and some voltage vector $\bar{V}_s\Delta t$ is applied then the resultant will give the $\bar{\psi}_s$ required value of flux. Hence we are able to control stator flux. The angle between the stator and rotor flux is automatically being controlled and hence the torque is controlled. Let the flux vector at t=0 is in sector I and both flux and torque have to increased i.e. dψ=1 and dm=1 then from Fig.4 we can analyze that the vector V2 should be applied so as to get the resultant flux vector.

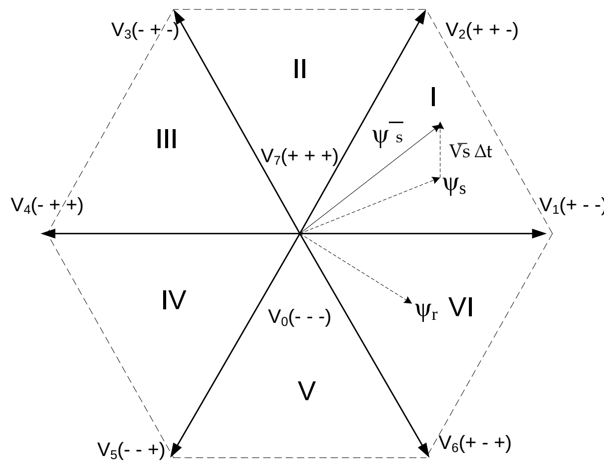

Fig.4 Output voltage vectors.

If only flux has to be increased keeping torque constant then the angle between stator and rotor flux should not be changed for this we have to apply the zero voltage vector hence for dψ=1 and dm=0 the vector V_7 has to be applied. The voltage vector should be decided such that the inverter has minimum number of switching. The fig.4 shows the look-up table for the proper selection of voltage switching vector.

Flux Status	Torque Status	Sectors					
		I	II	III	IV	V	VI
dψ=1	dm=1	V_2	V_3	V_4	V_5	V_6	V_1
	dm=0	V_7	V_0	V_7	V_0	V_7	V_0
	dm=-1	V_6	V_1	V_2	V_3	V_4	V_5
dψ=0	dm=1	V_3	V_4	V_5	V_6	V_1	V_2
	dm=0	V_0	V_7	V_0	V_7	V_0	V_7
	dm=-1	V_5	V_6	V_1	V_2	V_3	V_4

Fig.5 Voltage Switching Vector Look-up table.

6 MATLAB/SIMULINK MODEL

The main element of the simulink block of DTC has toque and flux calculator block, flux and torque hysteresis block, switching table block and switching control block. To estimate the motor flux d-q components and electromagnetic torque the torque and flux calculator block is used. A two-level hysteresis comparator for flux control and three-level hysteresis comparator for the toque control are enclosed in the flux and torque hysteresis block. The

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switching table has look-up tables in it for the proper selection of voltage vector according to the output of the flux and torque hysteresis comparison. To limit the inverter commutation frequency switching control block is used.

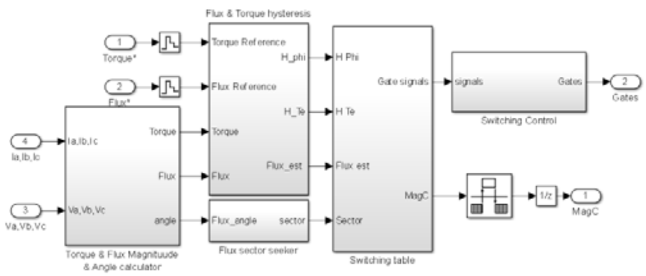

Fig.6 Simulink Model for DTC

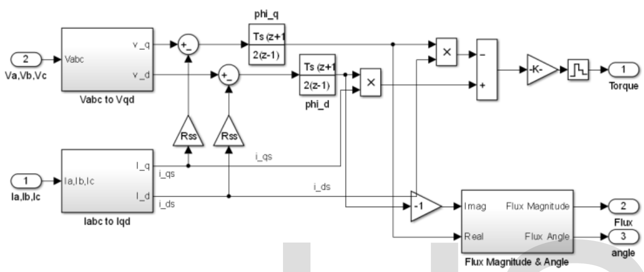

Fig.7 Torque, Flux Magnitude and Angle Calculator.

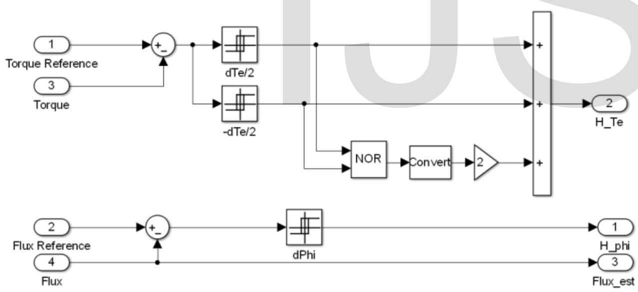

Fig.8 Flux and Torque Hysteresis.

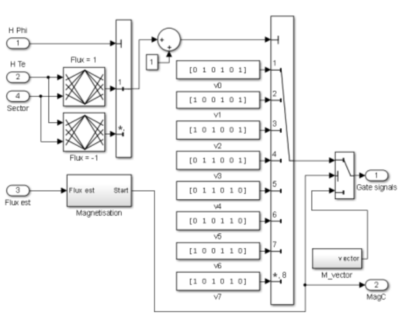

Fig.9 Simulink Model for Switching Table.

7 SIMULATION RESULTS

For Simulation and software program of a 3 Ph, 400V, 50Hz, 1430RPM and 4kW Induction Motor MATLAB R2013a is used. The result of electromagnetic torque and stator current are with respect to time. From the results we can analyze that, the torque and stator flux is controlled with the help of DTC-SVM scheme. The circular path is offered by DTC. The results obtained are as given below

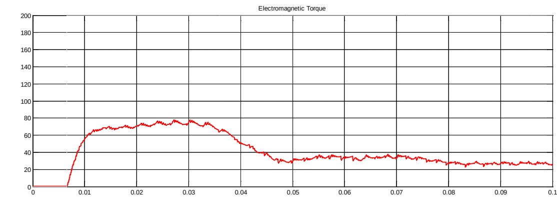

Fig.10 Electromagnetic Torque.

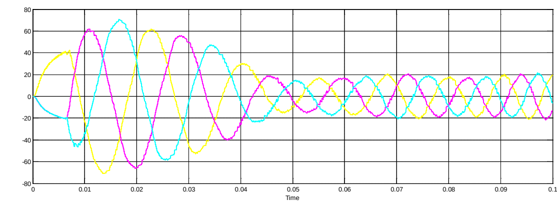

Fig.11 Stator Currents Ia,Ib,Ic.

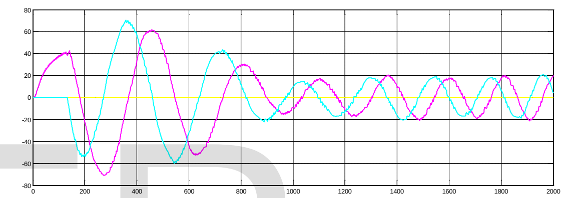

Fig.12 Stator Currents Id and Iq.

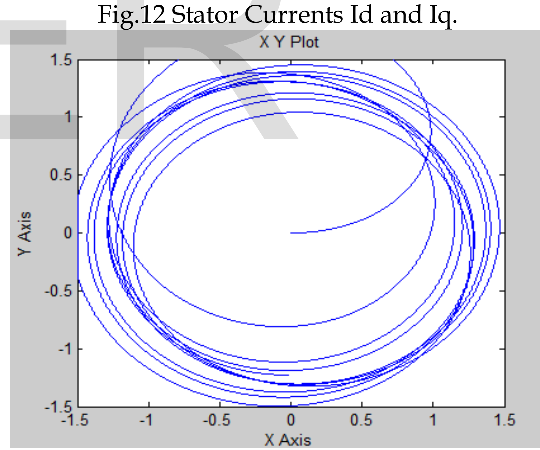

Fig.13 Stator Flux without DTC.

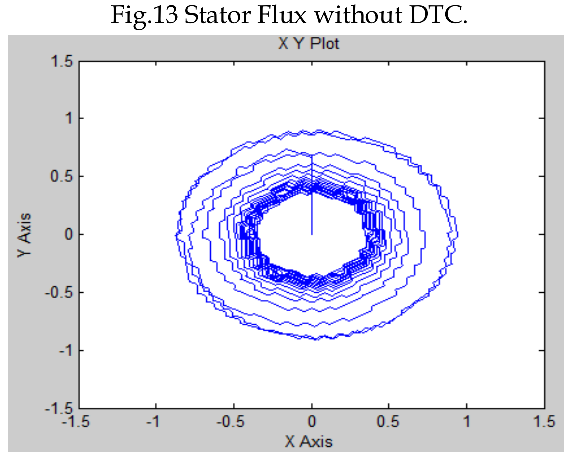

Fig.14 Stator Flux with DTC

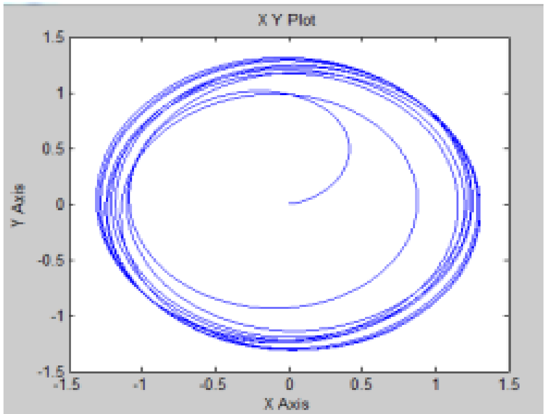

Fig.15 Rotor Flux without DTC.

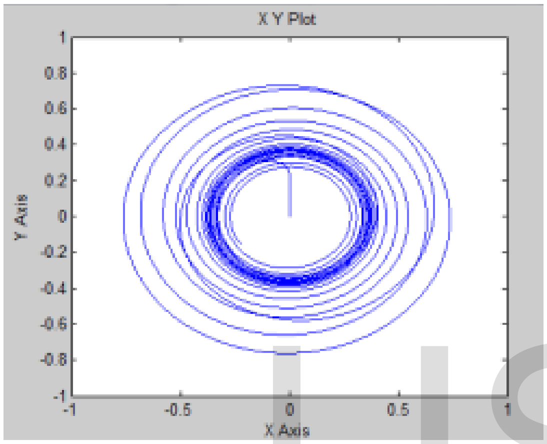

Fig.16 Rotor Flux with DTC.

8 Conclusion

The DTC-SVM technique is presented in this paper. The DTC-SVM method gives the fast torque response. Reduction in torque and flux ripple can be seen from the obtained results of DTC-SVM. For driving an Induction motor the Direct Torque Control is the better controller among the others. The performance of DTC is better for various applications and is flexible. Variable transformation and current loops can be avoided. Also speed sensor can be neglected. High stator flux linkage is the drawback of conventional DTC technique. Even at low speed it provides fast and accurate control. Direct torque and flux can be controlled effectively with the help of DTC-SVM.

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