Direct Torque and Flux Control of Induction Motor for Two Level Inverter

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Abstract- *At present induction motors are the dominant drives in various industries around the world, owing to their rugged construction and easy maintenance. However, it is quite cumbersome to control an induction motor because of its poor dynamic response in comparisons to DC motor drives. Direct torque and flux control of induction motor has emerged over he last decade to become one possible alternative to the well known vector control of induction motor. Direct torque control (DTC) is said to one of the future ways of controlling induction motor in four quadrants. And it does need long computation time, can be implemented without speed sensors and is insensitive to parameter variation. The study is done by using simulation by using simulink. This paper describes the control of induction motor using classical DTC (direct torque control) where the stator flux and torque are controlled directly by selecting the appropriate states of a two level inverter with the help of transient response in torque and stator flux linkages. This paper presents controlling the induction machine in four quadrants DTC has emerged over the last decade to become one possible alternative to the well-known Vector Control of Induction machines as it is a control technique in ac drive system to obtain high dynamic torque performance. The induction motor modelling and implementation of classical DTC control scheme using simulation and also those simulation results are presented in the paper.*

Keywords- DTC, Induction motor modelling, Two level voltage source inverter.

I. INTRODUCTION

Direct Torque Control (DTC) has emerged over the last decade to become one possible alternative to the well-known Vector Control of Induction machines. Its main characteristic is the good performance, obtaining results as good as the classical vector control but with several advantages based on its simpler structure and control diagram. AC asynchronous motor, also called as induction motor has become the most widespread electrical motor in use today. These facts are due to the induction motors advantages over the rest of the motors. The main advantage they do not need any mechanical commutator, leading to the fact that they are maintenance free motors. Induction motors also have low weight and inertia, high efficiency and a high overload capability. Therefore, they are cheaper and more robust, and less proves to any failure at high speeds. Furthermore, the motor can work in explosive environments because no sparks are produced. However, mechanical energy is more than often required at producing an infinitely variable induction motor speed drive is to supply the induction motor with the three phase voltages of variable frequency and variable amplitude. A variable frequency is required because the rotor speed depends on the speed of the rotating magnetic field provided by the stator. A variable voltage is required because the motor impedance reduces at low frequencies and consequently the current has to be limited by means of reducing the supply voltages.

II. THEORITICAL ANALYSIS

INDUCTION MOTOR MODELLING:

DTC is said to be one of the future ways of controlling the induction machine in four quadrants. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state. DTC main features are as follows:

- Direct control of flux and torque.
- Indirect control of stator currents and voltages.
- Approximately sinusoidal stator fluxes and stator currents. High dynamic performance even at stand still.

The main advantages of DTC are:

- Absence of co-ordinate transforms.
- Absence of voltage modular block, as well as other controllers such as PID for motor flux and torque.
- Minimal torque response time, even better than the vector controllers.

Disadvantages are also present such as:

- Possible problems during starting.
- Requirement of torque and flux estimators, implying the consequent parameters identification. Inherent torque and stator flux ripple.

Initially the theory of induction machine model is given. The understanding of this model is mandatory to understand both the control strategies (i.e. FOC and DTC). The theoretical details of vector control .This part will elaborately discuss the Vector control. After this, comparison of variable speed drives is given. The analysis of Direct Torque Control (DTC) strategy will take place..

Torque Expressions with Stator & Rotor Fluxes

The torque expression for induction machine can be expressed in vector form as,

$$\bar{T}_e = \frac{3}{2}\left(\frac{P}{2}\right)\bar{\psi}_s \bar{I}_s$$

Where $\bar{\psi}_s = \psi_{qs}^s - j\psi_{ds}^s$ & $\bar{I}_s = i_{qs}^s - ji_{ds}^s$. In this equation, $\bar{I}_s$ is to be replaced by rotor flux $\bar{\psi}_r$. In the complex form, $\bar{\psi}_s$ and $\bar{\psi}_r$ can be expressed as function of currents as,

$$\bar{\psi}_s = L_s\bar{I}_s + L_m\bar{I}_r$$

$$\bar{\psi}_r = L_r\bar{I}_r + L_m\bar{I}_s$$

$$\bar{\psi}_s = \frac{L_m}{L_r}\bar{\psi}_r + L_s^{'}\bar{I}_s$$

where $L_s^{'} = L_sL_r - L_m^{\ 2}$

$$\bar{I}_s = \frac{1}{L_s^{'}}\bar{\psi}_s - \frac{L_m}{L_rL_s^{'}}\bar{\psi}_r$$

$$\bar{T}_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_rL_s^{'}}\bar{\psi}_r\bar{\psi}_s$$

$$\bar{T}_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_rL_s^{'}}|\bar{\psi}_r||\bar{\psi}_s|\sin\gamma$$

Where γ is the angle between the fluxes.

Vectors $\bar{\psi}_s$, $\bar{\psi}_r$, and $\bar{I}_s$ for positive developed torque. If the rotor flux remains constant and stator flux is changed incrementally by stator voltage $\bar{V}_s$ as shown and the corresponding change of γ angle is $\Delta\gamma$, the incremental torque $\Delta\bar{T}_e$ expression is given as

$$\Delta\bar{T}_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_rL_s^{'}}|\bar{\psi}_r||\bar{\psi}_s + \Delta\bar{\psi}_s|\sin\Delta\gamma$$

$$V_{qs}^s = R_s I_{qs}^s + \frac{d}{dt}\psi_{qs}^s$$

$$V_{ds}^s = R_s I_{ds}^s + \frac{d}{dt}\psi_{ds}^s$$

$$V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e\psi_{ds}$$

$$V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e\psi_{qs}$$

If the rotor is not moving, that is, $\omega_r = 0$, the rotor equations for a doubly fed wound-rotor machine

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_e\psi_{dr}$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_e\psi_{qr}$$

Where all the variables and parameters are referred to the stator. Since the rotor actually moves at speed ω_r, the d - q axes fixed on the rotor move at a speed ω_e - ω_r relative to the synchronously rotating frame. Therefore, in $d^e - q^e$ frame, the rotor equations should be modified.

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr}$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr}$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_m & (\omega_e - \omega_r)L_m & R_r + SL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & SL_m & -(\omega_e - \omega_r)L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

$$T_e = T_L + J\frac{d\omega_m}{dt} = T_L + \frac{2}{P}J\frac{d\omega_r}{dt}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\overline{\psi}_m \bar{I}_r \sin\delta$$

DYNAMIC MODEL STATE-SPACE EQUATIONS

$$v_{qs} = R_s i_{qs} + \frac{1}{\omega_b}\frac{dF_{qs}}{dt} + \frac{\omega_e}{\omega_b}F_{ds}$$

$$v_{ds} = R_s i_{ds} + \frac{1}{\omega_b}\frac{dF_{ds}}{dt} + \frac{\omega_e}{\omega_b}F_{qs}$$

$$0 = R_r i_{dr} + \frac{1}{\omega_b}\frac{dF_{dr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b}F_{qr}$$

$$0 = R_r i_{qr} + \frac{1}{\omega_b}\frac{dF_{qr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b}F_{dr}$$

The feedback flux and torque are calculated from the machine terminal voltages and currents. The signal computation block also calculates the sector number *S(k)* in which the flux vector ψ_s lies. There are six sectors.

III. DIRECT TORQUE CONTROL (DTC)

In addition to vector control systems, instantaneous torque control yielding fast torque response can also be obtained by employing direct torque control. Direct torque control was developed more than a decade ago by Japanese and German researchers (Takahashi and Noguchi 1984, 1985; Depenbrock 1985). Drives with direct torque control (DTC) are being shown at great interest, since ABB has recently introduced a direct-torque controlled induction motor drive, which according to ABB can work even at zero speed. This is a very significant industrial contribution, and it has been stated by ABB that 'direct-torque control (DTC) is the latest a.c. motor control method developed by ABB' (Tiitien 1996). It is expected that other manufacturer will also release their DTC drives and further developments are underway for speed-sensor less and artificial intelligence based implementations.

In a DTC drive, flux linkage and electromagnetic torque are controlled directly independently by the selection of optimum inverter switching modes. The selection is made to restrict the flux linkages and electromagnetic torque errors within the respective flux and torque hysteresis bands, to obtain fast torque response, low inverter switching frequency and low harmonic losses. The required optimal switching vectors can be selected by using so-called optimum switching-voltage vector look-up table. This can be obtained by simple physical considerations involving the position of the stator-flux linkage space vector, the available switching vectors, and the required torque flux linkage.

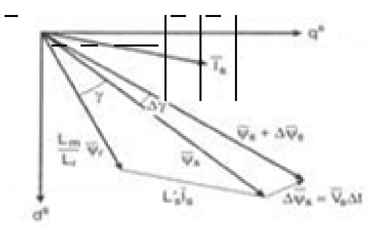

Figure.1 Stator flux, rotor flux, and stator current vectors on d_s-q_s plane.

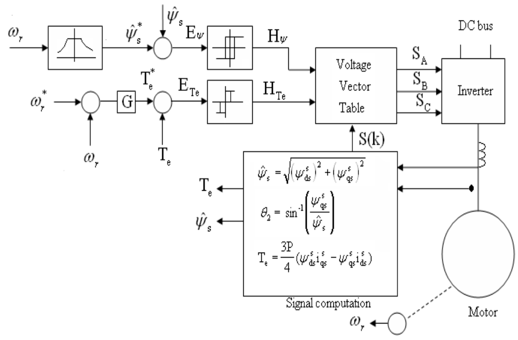

Figure2: Direct torque and flux control block diagram

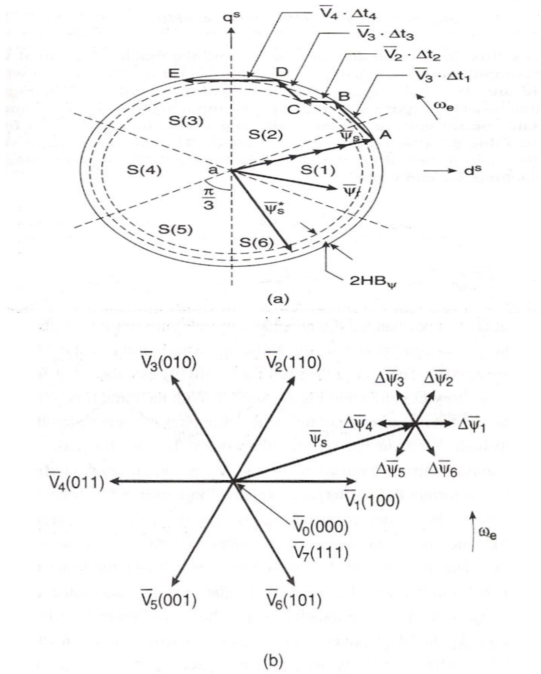

Figure 3: a) Trajectory of stator flux vector in DTC control, (b) Inverter voltage vectors and corresponding stator flux variation in time Δt.

The voltage vector table block in Figure3 receives the input signals H_{ψ}, H_{Te}, and *S(k)*and generates the appropriate control voltage vector (switching states) for the inverter by lookup table, which is shown in table 2 (the vector sign is deleted). The inverter voltage vector (six active and two zero states) and a typical $\overline{\psi}_s$ are shown in Figure 3(b). Neglecting the stator resistance of the machine, we can write

$$\overline{V}_s = \frac{d}{dt}(\overline{\psi}_s)$$

$$\Delta\overline{\psi}_s = \overline{V}_s . \Delta t$$

Which means that $\overline{\psi}_s$ can be changed incrementally by applying stator voltage $\overline{V}_s$ for time increment Δt. The flux increment vector corresponding to each of six inverter voltage vectors is shown in Figure 3(b). The flux in machine is initially established to at zero frequency (dc) along the trajectory OA shown in Figure 3(a). With the rated flux, the command torque is applied and the $\overline{\psi}_s^*$ vector starts rotating. Table 2 applies the selected voltage vector, which essentially affects both the torque and flux simultaneously. The flux trajectory segments AB, BC, CD and DE by the respective voltage vectors $\overline{V}_3, \overline{V}_4, \overline{V}_3$, and $\overline{V}_4$ are shown in Figure 3 (a). The total and incremental torque due to $\Delta\overline{\psi}_s$ are explained in previous section. Note that the stator flux vector changes quickly by, but the $\overline{\psi}_r$ change is very sluggish due to large time constant T_r. Since $\overline{\psi}_r$ is more filtered, it moves uniformly at frequency ω_e , whereas ψ_s movement is jerky. The average speed of both, however, remains the same in the steady-state condition. Table 2 summarizes the flux and torque change (magnitude and direction) for applying the voltage vectors for the location of $\overline{\psi}_s$ shown in Figure 3.(b). The flux can be increased by the $\overline{V}_1, \overline{V}_2$, and $\overline{V}_6$ vectors (vector sign is deleted), whereas it can be decreased by the $\overline{V}_3, \overline{V}_4$, and $\overline{V}_5$ vectors. The average speed of both, however, remains the same in the steady-state condition. Table2 summarizes the flux and torque change for applying the voltage vectors.

Table.1 switching table of voltage vectors [4]

H_ψ	H_T	S1	S2	S3	S4	S5	S6
1	1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V6	V1	V2	V3	V4	V5
-1	1	V3	V4	V5	V6	V1	V2
	0	V7	V0	V7	V0	V7	V0
	-1	V5	V6	V1	V2	V3	V4

Table.2 Flux and Torque variations [3]

Voltage vector	V1	V2	V3	V4	V5	V6	V0 or V7
Ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

From table2, voltage V_4 is applied to the inverter, which will generate the trajectory BC. The drive can easily operate in the four quadrants, and speed loop and field-weakening control can be added, if desired. The torque response of the drive is claimed to be comparable with that of a vector-controlled drive.

IV. SIMULINK MODEL OF INDUCTON MOTOR

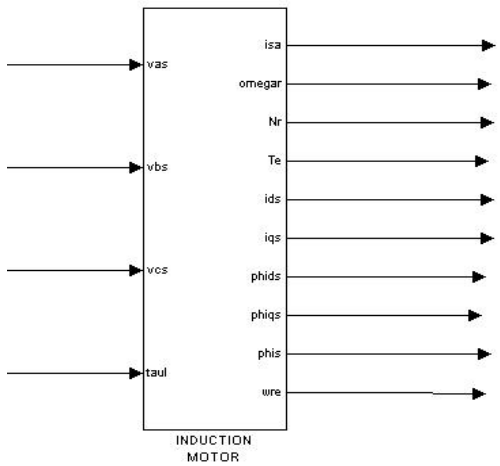

Figure .4 Induction motor block

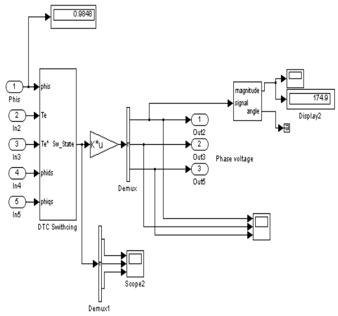

Figure 5: Subsystem2 block

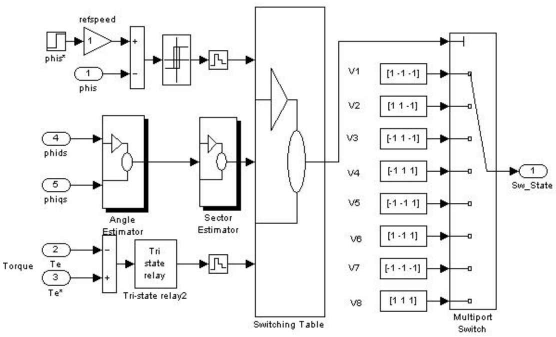

Figure.6 DTC switching block

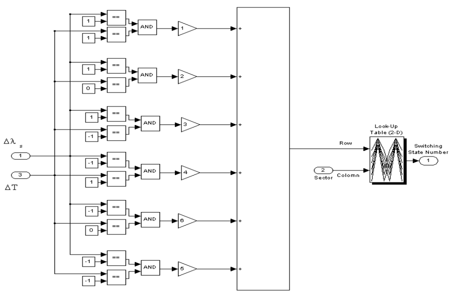

Figure 7: Sector estimator block

V. SIMULINK DIAGRAM OF DTC OF INDUCTION MOTOR

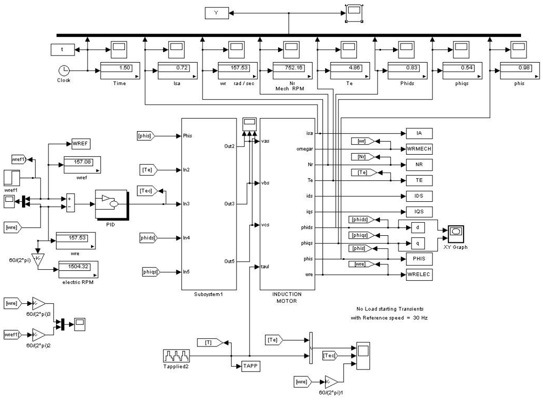

Figure 8: Switching table block

VI. SIMULATION RESULTS

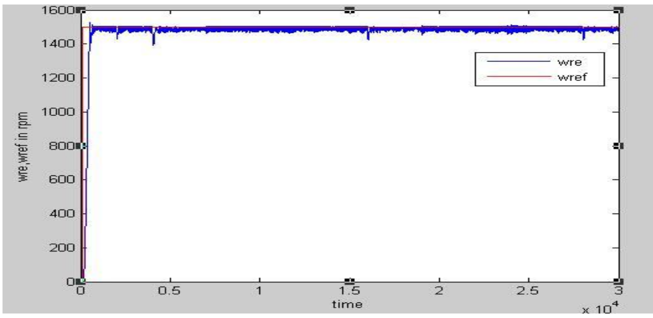

Figure9.Speed response of induction motor when reference speed is maintained constant

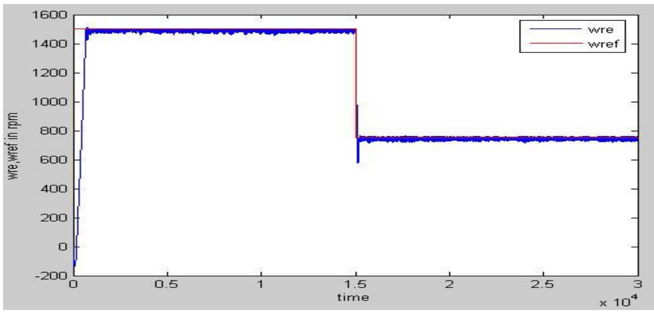

Figure10 Speed variation of IM at 0 to 1.5 sec

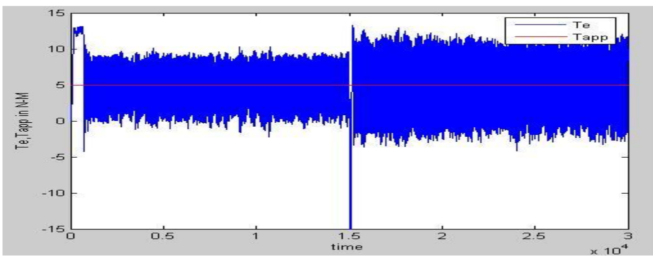

Figure11 Torque response of induction motor when load is constant

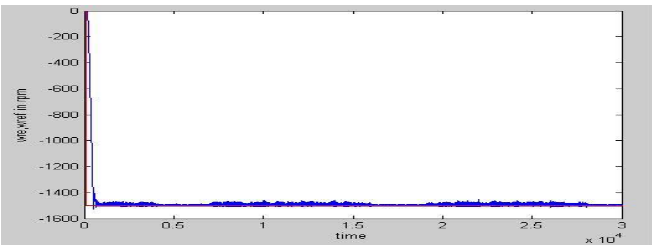

Fig 12 Speed response of induction motor when speed is reversed

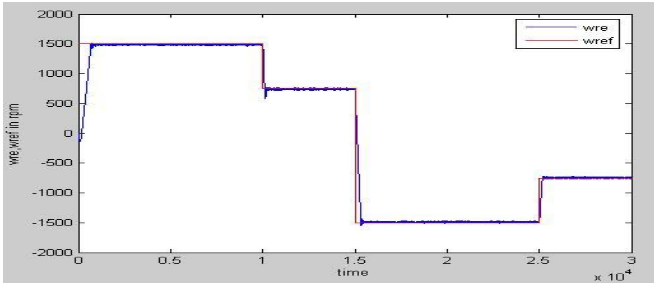

Figure13 speed response of IM when speed is in forward and reverse direction

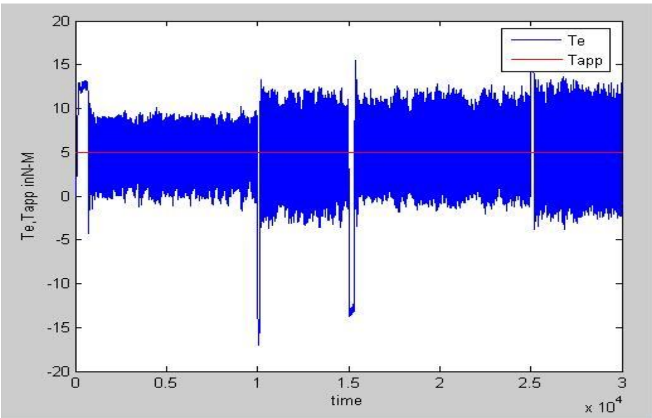

Figure14Torque response of induction motor when load is constant

VII. CONCLUSION

The simulation results shows that torque and speed responses are very good dynamic torque response for the direct torque control of the induction motor in forward and reverse speed directions. A direct torque control of induction motor is developed in Simulink environment. Its dynamic performances have been subjected to sudden changes in load and reference speed. With DTC scheme employing a voltage source inverter (VSI), it is possible to control directly the stator flux linkage and the electromagnetic torque by optimum selection of inverter switching vectors. The selection of inverter switching vector is made to restrict the flux and torque errors within the respective flux and torque hysteresis bands. This achieves a fast torque response. DTC-SVM strategy realizes minimum ripple free operation for the entire speed range. Consequently, the flux, torque and speed estimation is improved. The switching frequency is constant and controllable. In fact, the better results are due to the increasing of the switching frequency. While for DTC a single voltage vector is applied during one sampling time, for DTC–SVM a sequence of six vectors is applied during the same time. This is the merit of SVM strategy. The DTC-SVM controller does not depend on motor parameters and is relatively robust as was proved by simulation. The developed model is used load can be changed in short interval of time.

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