Direct Torque Control Of Induction Motor Drives – A Study

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ABSTRACT

Background: Motion control is imparted in the industrial drives to achieve both quality and quantity. DC drives were employed due to its superiority of control over the wide speed ranges, later the development of power electronics consents to the use of induction motor drives (IMD). Field Oriented Control (FOC) and Direct Torque Control (DTC) are the two strategies implemented to the IMD for speed control.

Objective: To study the modified methodologies intended in DTC and to analyze the best control strategy.

Results: Different control structures implemented so far to the IMD for the reduction of torque ripples are studied and the merits of applying DTC are discussed. Conclusion: The basic DTC schemes use an active voltage vector, whereas the modified DTC schemes utilize the adjacent active voltage vectors of the selected sector and two null or zero voltage vectors in a sampling period. In this study, it is concluded that the utilization of adjacent active vectors and null voltage vectors can improve the dynamic performance of the IMD.

INTRODUCTION

There is necessitate of continuous monitoring and control of industrial drives to use the available sources of energy in the most economical way (Benudhar Sahu et al., 2010). The requirements for automatic control in the process industries are increased significantly due to the increased complexity of the plants and sharper specification of product quality. To obtain the desired quality in the outcome motion control is imparted in the industrial drives (Lamia Youb and Aurelian Craciunescu, 2007). DC motor drive with Ward – Leonard speed control system was ascertained and they are quickly replaced with IMD due to the rapid development of power converter (Donald Grahame Holmes et al., 2012).

To acquire superiority in speed control the modern industries are revolutionized and alternately several advancements were originated in the control areas. More complex control logics being implemented due to the availability of fast acting computers and digital signal processors since a digital computer comprise the ability to control more than four hundred parameters efficiently. In this study an over view of control structures empowered in the industrial drives are conversed.

Control Structure:

Normally feedback control mechanism was employed because it is difficult to predict and measure the disturbance. The control structure implemented in the plants to achieve stable operation is shown in Fig. 1. It is the basic control structure put in practice for both AC and DC drives.
Fig. 1: FEEDBACK CONTROL STRUCTURE

Where, r(t) = set value
e(t) = error signal
u(t) = manipulated variable
c(t) = controlled variable

Independently energized DC drives are so simple in control (Boulghasoul et al., 2010) because they alone control flux, if it is maintained constant, provides an independent control of torque. Where as in AC machines simplicity in control is not like DC machines, which requires a coordinated control of stator current magnitudes, frequencies and their phases making complex in control. Due to the exponential growth in control areas high performance controls (Malik Elbuluk, 2003) such as FOC (Aengus Murray et al., 2008) and later the DTC (Yongchang Zhang et al., 2012) were implemented for the IMD with several modifications.

Field Oriented Control:

FOC has two types: Direct vector control (DVC) and Indirect flux vector orientation. In DVC, the flux vector is obtained by measuring stator terminal quantities, whereas in indirect control, the slip frequency of the motor is used to achieve the field orientation (Boulghasoul et al., 2010). FOC algorithm consent good dynamic control of torque and provides better performance over a wide speed ranges by field weakening (Aengus Murray et al., 2008). It makes independent control of flux and torque (Jannati and Fallah, 2010) like in DC machines, by supplying variable stator voltage to the induction motor (IM) to provide the desired motor torque and flux. Seeing that, the rotor flux is a function of the d-axis current and motor torque is the products of rotor flux and q-axis current.

Implementation of vector control also called FOC requires instantaneous rotor flux phasor (λr) position and the field angle (θf) (Krishnan. R, 2008). In terms of the synchronous speeds (ωs) and time (t) the θf is written as

\[ θ_f = \int ω_s \, dt \]  

The algorithm to be followed are given bellow

- Acquire the field angle θf
- Estimate the flux producing component of current, i_d* for a requisite λ_r*
- Calculate the torque producing component of stator current, i_q* from λ_r* and the required T_e* which gives an independent control of electromagnetic torque
- Find the stator current phasor magnitude, i_* from the vector sum of i_d* and i_q*
- Calculate the torque angle, θ_r

\[ θ_r = \tan^{-1}(i_q*/i_d*) \]  

Find θ_i from θ_r and θ_o, using this θ_o and i_d* the required stator current commands are calculated by going through the qd0 transformation to abc variables:

\[ I_{d*} = i_d* \sin θ_i \]  
\[ I_{b*} = i_d* \sin (θ_i - 120) \]  
\[ I_{c*} = i_d* \sin (θ_i + 120) \]
These stator phase current requests are simplified with inverter and current feedback loops. The phase current control loops may use either pulse width modulation or hysteresis or space vector modulation techniques for the switching. The function of FOC greatly depends on the machine parameters, in order to reduce the dependency and to improve the dynamic response the DTC was introduced (Yongchang Zhang et al., 2012).

**Direct Torque Control:**

The functional block diagram of the DTC is shown in Fig.2. The DTC concepts are easy to implement in the real time and it does not entail the coordinate transformations. Here the torque and the flux are estimated based on the measurement of stator current and $V_{dc}$ as feedback, they are compared with theirs set values. The torque and flux errors are compared with the flux and torque hysteresis controllers. Based on the range of errors and sector angle $\theta_s$, appropriate switches have been made to conduct in order to minimize these errors.

![Functional Diagram of DTC](image)

**Fig. 2: FUNCTIONAL DIAGRAM OF DTC**

The DTC has several benefits such as, Ability to produce fast torque control, fast flux control, provides good performance over a wide speed ranges without using any use of coordinate transformations, estimates the flux, torques from the stator currents with robust motor parameters, no need of position or speed sensors etc.

Even though it has several benefits, it has some drawbacks. They are, the use of high speeds modified switching table leads losing of flux control in a wide area, results inefficient operation, variable switching frequency operation, difficult to implement in digital control, difficult to control the torque at reduced speeds and the variation of stator resistance due to temperature rise degrades the performance over its control.

**Study of DTC:**

Here, the DTC methods employed in IM drives are discussed. To obtain fast torque response a switching table is employed to select optimum inverter voltage vector (Malik Elbuluk, 2003). For a given speed, to change the electromagnetic torque at a faster rate the magnitude of stator flux linkage is kept unvarying and the sector angle is to be changed rapidly. Based on position of the stator flux, an optimum switching table is designed for picking up the suitable voltage vector to control the torque and flux.

The stator flux linkage is related with the applied voltage (7), thus required flux is obtained by choosing the appropriate inverter switching state because the changes in flux and torque are the functions of applied voltage and switching time of the inverter.

$$\lambda_{qds} = L_q i_{qds} + L_m i_{qdr}$$  \hspace{1cm} (6)

$$v_{qds} = i_{qds} R_s + \frac{d}{dt} \lambda_{qds}$$  \hspace{1cm} (7)

The stator flux linkage shifts in space in the direction of stator voltage vector, thus by selecting the appropriate voltage vector it is then possible to change the stator flux in the required way.

**Case (1). Torque Ripple Minimization in Direct Torque Control of Induction Machines:**

Malik Elbuluk presented the fuzzy logic based duty ratio control scheme to reduce the torque ripples, proven that an improved steady state torque response is achieved by this method. Instead of applying voltage vector continuously for the entire switching period a zero switching state vector is applied for some period to minimize the torque ripples. The nonzero voltage vector period is called duty ratio ($\delta$), the $\delta$ value varies...
between 0 and 1. During the period of zero voltage vector switching, no voltage is applied, the average voltage applied in each switching state is given by

\[ v_s = \delta v_{dc} \]  \hspace{1cm} (8)

### Case (2). Combined Vector Control and Direct Torque Control an Experimental Review and Evaluation:

New scheme for speed control is called combined vector control and DTC was proposed by Boulghasoul et al., for control of torque, which uses the benefits of both FOC and DTC. It has the current vector control and switching table. Using this combination the PI controller is replaced with hysteresis controller and the pulse width modulation (PWM) signals by switching table.

The objective of FOC is independent control of flux and torque as like in DC machines, this is achieved by using d - q reference frame rotating synchronously with rotor flux space vector. Where as in DTC the flux and the torque are controlled directly by applying appropriate voltage vector among the six equally spaced constant amplitude voltage vector combinations (001 – 110 except 000 and 111) in which ‘1’ represents upper switch is ‘ON’ and ‘0’ indicates the lower switch is ‘ON’ in a leg. Stator flux \( \Phi_s \) is controlled on the control of applied stator voltage \( v_s \) and hence, the rotor flux \( \Phi_r \) by \( \Phi_s \).

The electromagnetic torque is given by,

\[ T_e = P \frac{L_m}{\omega s} \Phi_r \Phi_s \sin \alpha \]  \hspace{1cm} (9)

\[ \frac{dT_e}{dt} = k \frac{d\Phi_r}{dt} \sin \alpha \]  \hspace{1cm} (10)

Where,

\( P \) = pole pairs

\( L_m, s, r \) = Mutual, stator and rotor inductances

\( \Phi_s, r \) = Stator and rotor fluxes

\( \sigma = (1 - L_m^2)/(L_s L_r) \) = Total leakage factor.

\( \alpha = \) Angle between stator and rotor fluxes

\( k = P \frac{L_m}{\omega s} \Phi_r \Phi_s \)

Equation (9) shows the variation of ‘\( \alpha \)’ allows control of torque and is achieved by applying appropriate voltage vector among any one of the six active voltage vectors. The torque and flux are controlled by using hysteresis loops.

### Case (3). A Modified Direct Torque Control for Induction Motor Sensorless Drive:

Cristian Lascu et al., presented DTC with Space Vector Modulation (SVM) based flux controller, the torque and flux control functions used are similar to DTC but the voltage is produced by SVM unit. It preserves the robustness of DTC with lower torque ripples and provides constant switching frequency operation. The estimator calculates the fluxes, torque and speed based on the IM equations with respect to the stationary reference frame. The full order flux estimator contains two modes: 1) open loop current model, meant to produce accurate values at low speed ranges and 2) an adaptive model for wide speed ranges.

The rotor flux estimator with respect to rotor flux reference frame is given by,

\[ \Psi_{std} = \frac{L_m}{1 + \frac{L_m}{R_s}} i_{std} \frac{S - \omega r}{1 + \frac{L_m}{R_s}} \]  \hspace{1cm} (11)

Where,

\( \omega_{ref} \) = Reference frame and rotor speeds

\( \Psi_r \) = Rotor flux

\( L_{r,m} \) = Rotor and mutual inductances

\( R_r \) = Rotor resistance

\( I_s \) = Stator current

The open loop current model based stator flux \( \Psi_s \) estimation is given by,

\[ \Psi_s = \frac{L_m}{L_r} \Psi_r + \frac{L_{r,m}}{L_r} I_s \]  \hspace{1cm} (12)
Where $\psi_{r\alpha}$ is the estimated rotor flux in a stationary reference frame and is obtained using the following relations.

\[
\psi_{rd} = \frac{L_m}{1+\frac{s}{\sigma}} i_{sd}\text{ and } \psi_{rq} = 0
\]  

(13)

The adaptive model is a current model represented by the following relation,

\[
\psi_{r\alpha} = \frac{L_m}{1+\frac{s}{\sigma}} i_{s\alpha} - \frac{\omega}{1+\frac{s}{\sigma}} \psi_{r\alpha}
\]  

(14)

This uses two PI controllers one for torque and the other for flux control with SVM unit. The SVM unit generates the inverter command signal based on these control signals. Cristian Lascu et al., were concluded that the DTC – SVM strategy provides ripple free operation for the entire speed ranges.

**Case (4). Direct Torque Control of Induction Motor Using Space Vector Modulation (SVM-DTC):** Emre Ozkop and Halil I. Okumus presented the SVM – DTC, many advantages of this method were discussed such as, SVM provide better DC bus utilization, lower switching loss, reduced total harmonic distortion, ease of implementation in digital systems, reduced torque ripples etc. Use of high number of voltage vector gives more accurate switching table, which provides tight control over the flux and torque in conventional DTC. But, due to the control, power circuit’s complexity the use of more number of voltage vectors are restricted and is restricted only to the high power applications. In SVM - DTC method the exact voltage space vector is estimated depends on the flux and torque errors using predictive technique and the vector is generated using SVM at every sampling period.

In the conventional DTC, a single voltage vector is applied for the entire sampling period. Where as in SVM instead of using one vector in a sampling period more than one vector is used and the slip frequency were controlled by applying zero state vectors with constant switching frequency. Its operation is based on toggle between two adjacent nonzero voltage vectors and zero voltage vectors in a sampling period of ‘T’ seconds. It is shown in Fig.3 for the third sector (120° – 180°). Equations (15) to (17) are holds good for the calculation of switching times and one transient state occurs in every switching state as shown in Fig.4.

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**Fig. 3:** Svm In The Iii Sector

**Fig. 4:** Switching Pattern For Three Phases
Fig. 4. Clearly represents the four states of voltage vectors corresponding to the voltages $V_0$, $V_3$, $V_4$ and $V_7$ (000, 010, 011 and 111) were applied in a sampling period of ‘T’ seconds in a sector, where as in DTC either $V_3$ or $V_7$ only be applied in a sector for a sampling period. The switching time $T_z$ is for both the zero state vectors $V_0$ and $V_7$. Simulation result illustrates on employment of this method, it maintains the benefits of DTC with reduced torque ripples.

**Case (5). Sensorless Direct Torque Control of Induction Motor based on Hybrid Space Vector Pulse width modulation to Reduce Ripples and Switching Losses – A Variable structure Controller Approach:**

Brahmananda Reddy et al., presented a seven zone hybrid space vector pulse width modulation (HSVPWM) technique to minimize the torque ripples. Here, for every sampling period, voltage vectors are generated to minimize the ripples. In the conventional SVPWM an average voltage vector, whose value same as the reference voltage is generated in every sampling period ‘T’. For a specified reference voltage and angle $\alpha$ in sector - III to maintain the volt – time balance the active state vectors 3,4 and two zero state vectors were applied for the durations $T_1$, $T_2$ and $T_z$ respectively. The time durations $T_1$, $T_2$ and $T_z$ are given by,

$$T_1 = 1.5 \frac{\text{vref}}{\text{vdc}} T \frac{\sin(\pi \tau - \alpha)}{\sin(\pi)}$$  \hspace{1cm} (15)

$$T_2 = 1.5 \frac{\text{vref}}{\text{vdc}} T \frac{\sin(\alpha)}{\sin(\pi)}$$  \hspace{1cm} (16)

$$T_z = T - (T_1 + T_2)$$  \hspace{1cm} (17)

For example in the third sector, the conventional SVPWM uses the switching sequence 0347 - 7430. Whereas here, it is subdivided into seven switching zones, the number of switching state in each sub – cycle is three or lesser as like in conventional SVPWM. The switching sequences are given bellow.

- 0347 -7430 (Common switching)
- 034 -430 (S1) and 743 -347 (S2)
- 0343 – 3430 (S3) and 7434 – 4347 (S4)
- 3034 – 4303 (S5) and 4743 – 3474 (S6)

The sequence of switching is from $S_1$ to $S_6$ which cause there is a decrease in torque ripples and switching losses of the inverter.

**Case (6). A combined model predictive control/space vector modulation (MPC-SVM) strategy for direct torque and flux control of induction motors:**

In this work a combined Model Predictive Control (MPC) - SVM is designed to the control of torque and flux for an induction motor. The appropriate sequence of voltage vectors are used instead of using single voltage vector over a sampling period. Selection of appropriate sequence of voltage vector at every sampling instant is done by the minimization of cost functions that minimizes the torque and flux errors over the specified prediction horizon. MPC computes the optimal control input to be applied based on the current state of the plant and future states predicted over the specified prediction horizon using the plant model. The objective of MPC is to replace the switching table by some optimization algorithms, which uses the predicted output of the plant model over the specified time. By appropriate creation of voltage vector sequence over the specified horizon with constant duration provides controls having SVM property, which is the constant frequency operation of the inverter.

In SVM technique, a reference voltage $v^* (t)$ is provided to produce the switched three phase voltage waveform, such that the time average of the first order harmonic component is same as the time average of this reference signal. To achieve this, here the $v^* (t)$ is sampled at the rate of $2f_s = 1/T$ and the sampled value is say $v^* (t_i)$, is used to solve the equations:

$$v^* (t_i) = (1/T) (T_1 v_7 + T_2 v_8 + T_z v_0)$$  \hspace{1cm} (18)

$$T_z = T - (T_1 + T_2)$$  \hspace{1cm} (19)

Where, $v_{0,7}$ is the zero voltage vector, $v_7$ and $v_8$ are the active voltage vectors adjacent in space to the reference voltage vector $v^* (t_i)$.

Here, it utilizes the MPC technique with voltage vectors of dissimilar magnitudes approximately combined to produce the sub cycles of constant time duration over a sampling period ‘T’. The general pattern of the control action sequence is as shown in Fig.5.
The voltage vector sequence applied over a sampling period 'T' is subdivided into several subsets of combinations of two adjacent active voltage vectors, it is possible to select an ordered combination of vectors as: \((V_1, V_2), (V_3, V_2), (V_4, V_3), (V_5, V_3), (V_5, V_6), (V_1, V_6)\) and zero voltage vectors \((V_0\text{ and } V_7)\). It uses the null voltage vector \(V_7\) in the middle, \(V_0\) at both the ends. Active vectors are used in the remaining part left to the \(V_7\) and the same are used its right side in the reverse order. Odd sub indexed vectors are used first because, it involves one switch is being 'ON' at every instant. It gives switching similar to Fig. 4. Several sequences are possible in a segment over a period 'T' as shown in Fig.6 and Fig.7.

**Case (7). Low-Speed Control Improvements for a Two-Level Five-Phase Inverter-Fed Induction Machine Using Classic Direct Torque Control:**

In this work a low speed performance improvement of five phase \((n = 5)\) induction motor drive using two level inverter is presented. When the five phase IM runs at reduced speeds there is occurrence in demagnetization of stator flux, results poor performance, to overcome this phenomenon the displaced voltage...
vector of $\pm 36^\circ$ is applied at low speeds but $\pm 72^\circ$ displaced voltage vector otherwise. Five phase IM uses five legs so it has $2^5 = 32$ switching states of the inverter, the flux and torque producing components are effectively utilized so as to achieve the optimized stator flux regulation, results reduced torque ripples at reduced speeds. A low speed switching strategy is proposed, which selects an optimum voltage vector based on the machine speed. In this study the 32 states ($V_1$ to $V_{32}$) are distributed in the $d_1 - q_1$ and $d_3 - q_3$ planes as long (0.6472 $V_{dc}$), medium (0.4 $V_{dc}$), short (0.2472 $V_{dc}$) and null (zero) voltage vectors.

![Fig. 8: Inverter States In The d1 – q1 Vector Space](image)

![Fig. 9: Inverter States In The d3 – q3 Vector Space](image)

In Fig.8 it is observed that the voltage vectors have the same direction, whereas in Fig.9 the direction of the medium vector is opposite to the long and short vectors. This feature provides decrease and cancellation of $d_3 - q_3$ stator flux. Five voltage vectors are selected in every switching (Example: $V_{21}, V_{11}, V_1, V_6, V_{11}$ and $V_{26}$) period, the aim is to make the second product of $d_3 - q_3$ vector to be zero over the switching period. The highest vector length made in $d_3 - q_3$ vector plane is $0.526 V_{dc}$. At every switching period, an individual voltage vector is selected, and the highest resultant voltage vector magnitude of $0.553 V_{dc}$ is developed in the $d_1 - q_1$ vector space for the five-phase drive system. This increases the voltage vector by 5% using classic DTC than SVM - DTC. This can improve the torque and flux response significantly.

Case (8). An Improved Direct Torque Control for Three-Level Inverter-Fed Induction Motor Sensorless Drive:

A three level neutral point clamped inverter fed IM drive is presented in this work. The limitations of conventional DTC such as fail to consider the neutral point balance and smooth switching of voltage vectors are discussed. Fuzzy control and speed adaptive flux observer schemes are used to solve the said problems and to improve the system performance. Here two types of DTC methods are presented, in the first method, the DTC uses three level inverter directly and in addition an appropriate vector is inserted to overcome these limitations. The first vector is selected as per the demand, later the neutral point balance and smooth switching are considered. But this method has complex vector selection.

In method two, a sampling period ‘T’ is subdivided into two or three intervals to obtain more vectors. This method is similar to the case – 6 of this study.

Case (9). Direct Torque Control of Two-Phase Induction and Synchronous Motors:

DTC is with two, three and four leg inverters to the two phase induction motors and synchronous motors are presented by Saleh Ziaeinejad et al. The electrical time constant of induction motor rotor is large (Brahmananda Reddy et al., 2006), due to this reason rotor flux does not change in a short interval, for quick torque response it is suggested that the voltage vector is rotated in a way the $\theta_s$ would increase rapidly. Further if the stator flux vector is near to the border of a sector, the voltage vector component tangent to the circular route of the stator flux is very less, so it is not able to reduce the torque error results it is unable to keep the electromagnetic torque within the allowed band. To obtain good performance in the drives, high performance control is employed.

Conclusion:

In this study, different control structures implemented so far for the IMD are discussed. The merits and drawbacks of DTC are presented. Even though it has some limitations, still the study is carried in this topic, because as on now there is a lag in the universal control design for the IMD due to its nonlinear behaviour. Also it requires more complicated mathematical equations and transformations to obtain the accurate control law.

Several modifications are carried out in the basic DTC scheme to achieve better control over the range of speeds by controlling the flux and torque. In this study, it is found that case – 1 to case – 3 and case – 9 of this study use a single active voltage vector of constant magnitude over a sampling period ‘T’ and utilizes the benefits of basic DTC. Where as in case - 4 to case - 8 of this study, the sampling period ‘T’ is divided in to
several sub intervals, the circuit is switched between both the adjacent active voltage vectors in the selected sector and with zero or null voltage vectors. It is proven that the use of both active and null vectors in a sampling period of time ‘T’ provides variable voltage to the drive and it is possible to get better control. From this study it is concluded that the use of null voltage vector can improve the dynamic performance of the IM drives.

REFERENCES


