Direct Torque Control of Induction Motor with Fuzzy Controller: A Review

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Abstract: At present, induction motors are the dominant drives in various industries. It is quite cumbersome to control an induction motor (IM) because of its poor dynamic response in comparison to the DC motor drives. The central theme of Vector Control (VC) is to decouple the stator current of the IM into two orthogonal components and is to control these two components individually so as to achieve an independent control of flux and torque of the IM. VC is still very complex to implement. Direct Torque Control (DTC) is an improvised VC method. With the DTC scheme employing a Voltage Source Inverter, it is possible to control directly the stator flux linkage and the electromagnetic torque by the optimum selection of inverter switching vectors. The modeling of an IM drive employing DTC with application of fuzzy is performed in this article, it is better to understand the DTC and its difficulties. The reference voltage vector is then realized using a voltage vector modulator. Several variations of DTC-SVM have been proposed and discussed in the literature. The work of this review paper is to study, evaluate and compare the various techniques of the DTC-SVM applied to the Induction Motor.

Keywords: Induction Motor Drive, Modeling of Induction Motor, Vector Control, Field Orient Control, Direct Torque Control, and Fuzzy Applications.

1. INTRODUCTION

The history of electrical motors goes back as far as 1820, when Hans Christian Oersted discovered the magnetic effect of an electric current. One year later, Michael Faraday discovered the electromagnetic rotation and built the first primitive D.C. motor. Faraday went on to discover electromagnetic induction in 1831, but it was not until 1883 that Tesla invented the A.C. asynchronous motor [1]. Currently, the main types of electric motors are still the same, DC, AC asynchronous and synchronous, all based on Oersted, Faraday and Tesla’s theories developed and discovered more than a hundred years ago.

An IM is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction [2-5]. Induction motors are widely used, especially polyphase induction motors, which are frequently used in industrial drives. These facts are due to the induction motors advantages over the rest of the motors. Most of the industrial motor applications use AC induction motors. The reasons for this include high robustness, reliability, low price and high efficiency [2-8].

2. PRINCIPLE OF OPERATION AND COMPARISON TO SYNCHRONOUS MOTORS

A 3-phase power supply provides a rotating magnetic field in an IM. The basic difference between an IM and a synchronous AC motor is that in the latter a current is supplied onto the rotor. This then creates a magnetic field which, through magnetic interaction, links to the rotating magnetic field in the stator which in turn causes the rotor to turn. It is called synchronous because at steady state the speed of the rotor is the same as the speed of the rotating magnetic field in the stator. By way of contrast, the IM does not have any direct supply onto the rotor; instead, a secondary current is induced in the rotor [2, 9]. This changing magnetic field pattern can induce currents in the rotor conductors. These currents interact with the rotating magnetic field created by the stator and the rotor will turn [10].

This difference between the speed of the rotor and speed of the rotating magnetic field in the stator is called slip. The three phase AC IM and is the most widely used machine. Because it is having the characteristic features Simple and rugged construction, Low cost and minimum maintenance, High reliability and sufficiently high efficiency, Needs no extra starting motor and need not be synchronized, and an IM has basically two parts: Stator and Rotor [10].

2.1. APPLICATIONS

A wide variety of induction motors are available and are currently in use throughout a range of industrial applications. Single phase induction motors are widely used, due to their simplicity, strength and high performance. They are used in household appliances, such as refrigerators, air conditioners, hermetic compressors, washing machines, pumps, fans, as well as in some industrial applications. Before the days of power electronics, a limited speed control of IM was achieved by switching the three-stator windings from delta connection to star connection, allowing the voltage at the motor windings to be reduced [1-20].

2.2. VARIABLE-FREQUENCY DRIVES (VFD)

A VFD can easily start a motor at a lower frequency than the AC line, as well as a lower voltage, so that the motor starts with full rated torque and with no inrush of current. The rotor circuit's impedance increases with slip frequency, which is equal to supply frequency for a stationary rotor, so running at a lower frequency actually increases torque [21-23]. Industries have many applications, where variable operating speed is a prime requirement. Principal benefits of variable speed drives in industrial applications are that they allow the drive speed and torque to be adjusted to suit the process requirements. In many applications, operating the plant at a reduced speed when full output is not needed produces a further important benefit: energy savings and reduced cost [21]. Whereas infinitely variable speed drives with good performances for DC motors already existed. These drives not only permitted the operation in four quadrants but also covered a wide power range. Moreover, they had a good efficiency, and
with a suitable control even a good dynamic response. Its main drawback was the compulsory requirement of brushes [10].

The various methods of speed control of squirrel cage IM through semiconductor devices are given in [2, 9-20] as under: Scalar control, Vector control (Field-Oriented Control, FOC), Direct Torque Control (DTC) and DTC with SVM & Fuzzy based control. These controllers are depends on how inverters can be controlled, mostly multilevel inverters are using in industries due to their advantages [21-45].

Scalar controllers: Despite the fact that “Voltage-Frequency” (V/F) is the simplest controller, it is the most widespread, being in the majority of the industrial applications [2]. It is known as a scalar control and acts by imposing a constant relation between voltage and frequency, so as to give nearly constant flux over wide range of speed variation [9]. More over Constant voltage/hertz control keeps the stator flux linkage constant in steady state without maintaining decoupling between the flux and torque [2]. However, this controller does not achieve a good accuracy in both speed and torque responses, mainly due to the fact that the stator flux and torque are not directly controlled. Even though, as long as the parameters are identified, the accuracy in the speed can be 2% (expect in a very low speed), and the dynamic response can be approximately around 50ms [2, 9].

Vector controllers: In 1971, Blaschke propose a scheme which aims as the control of an IM like a separately excited dc motor, called field oriented control, VC, or Trans vector control [46-48]. In this scheme the IM analyzed from a synchronously rotating reference frame where all fundamental variables appears to be d or q ones. The torque and flux component of currents are identified and controlled independently to achieve good dynamic response [46, 47]. The most widespread controllers of this type are the ones that use vector transform such as either Park or Ku. However there is a necessity of transforming the variables in the synchronously rotating reference frame to stator reference frame to affect the control of actual currents/voltages [47]. Additionally the transformation also needs the approximate flux vector angle, where is either calculated slip angle or measured rotor angle as indirect VC or by estimating the flux angle directly by employing a flux observer as in direct VC [47]. Its accuracy can reach values such as 0.5% regarding the speed and 2% regarding the torque, even when at standstill. The main disadvantages are the huge computational capability required and the compulsory good identification of the motor parameters.

Recently advanced control strategies for PWM inverter fed IM drives have been developed based on the space vector approach, where the IM can be directly and independently controlled without any co-ordination transformation [48]. One of the emerging methods in this perspective is the direct torque and flux control (DTFC). In DTFC, the motor torque and the flux are calculated from the primary variables, and they are controlled directly and independently by selecting optimum inverter switch modes [2, 22-32]. This control results in quick torque response in the transient operation and improvement in the steady state efficiency [14]. 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.

DTC is said to be one of the future ways of controlling the IM in four quadrants. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state [46, 54]. DTC main features are direct control of flux and torque, indirect control of stator currents and voltages, approximately sinusoidal stator fluxes and stator currents, and High dynamic performance even at stand still [53, 54]. DTC have several advantages like, Decoupled control of torque and flux, Absence of co-ordinate transforms, Absence of voltage modular block, Absence of mechanical transducers, Current regulator, PWM pulse generation, PI control of flux and torque and co-ordinate transformation is not required, Very simple control scheme and low computational time, and Reduced parameter sensitivity and Very good dynamic properties as well as other controllers such as PID for motor flux and torque, and Minimal torque response time even better than the VCs [53, 54]. However, some disadvantages are also present such as: Possible problems during starting, Requirement of torque and flux estimators, implying the consequent parameters identification, and Inherent torque and stator flux ripple [53-54]. Although, some disadvantages are: High torque ripples and current distortions, Low switching frequency of transistors with relation to computation time, Constant error between reference and real torque [3].

After this, comparison of variable speed drives is given. The aim being to find even simpler methods of speed control for induction machines one method, which is popular at the moment, is DTC.

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). DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. Straightly speaking, Major drawback of Classical DTC is high torque & flux ripples. The most common solution to this problem is to use fuzzy applications with Space Vector Modulation (SVM) or using multilevel inverter [2, 3]. In this Paper the author briefly explained about two-fuzzy controller along with the SVM technique is applied to two level inverter. Before going to DTC, first we study about the mathematical background of DTC.

3. INDUCTION MOTOR MATHEMATICAL MODEL

The steady-state model and equivalent circuit are useful for studying the performance of machine in steady state. This implies that all electrical transients are neglected during load changes and stator frequency variations. The dynamic model of IM is derived by using a two-phase motor in direct and quadrature axes [55]. This approach is desirable because of the conceptual simplicity obtained with the two sets of the windings, one on the stator and the other on the rotor.

The equivalence between the three-phase and two-phase machine models is derived from the simple observation. The concept of power invariance is introduced [2, 3, 8]. The reference frames are chosen to arbitrary and particular cases such as stationary, rotor, and synchronous reference frames, are simple instances of the general case.
The space-phasor model is derived from the dynamic model in direct and quadrature axes [55].

3.1 DYNAMIC d-q MODEL

The assumptions are made to derive the dynamic model as uniform air gap, balanced rotor and stator windings, with sinusoidal distributed mmf, inductance vs. rotor position in sinusoidal, and Saturation and parameter changes are neglected.

The dynamic performance of an AC machine is somewhat complex because the three-phase rotor windings move with respect to the three-phase stator windings as shown in Fig 1(a). Basically, it can be looked on as a transformer with a moving secondary, where the coupling coefficients between the stator and rotor phases change continuously with the change of rotor position $\theta_r$, correspond to rotor direct and quadrature axes [2-4, 7, 8]. Note that a three-phase machine can be represented by an equivalent two-phase machine as shown in Fig 1(b), where $d' - q'$ correspond to stator direct and quadrature axes, and $d' - q'$ correspond to rotor.

![Fig 1: (a) Coupling effect in three-phase stator and rotor windings of motor; (b) Equivalent two-phase machine.](image)

Although it is somewhat simple, the problem of time-varying parameters still remains. R.H. Park, in the 1920s, proposed a new theory of electric machine analysis to solve this problem. Essentially, he transformed or referred, the stator variables to a synchronously rotating reference frame fixed in the rotor [56]. With such a transformation (called Park’s transformation), he showed that all the time-varying inductances that occur due to an electric circuit in relative motion and electric circuits with varying magnetic reluctances can be eliminated [3, 7]. Later, in the 1930s, H. C. Stanley showed that time- varying inductances in the voltage equations of an induction machine due to electric circuits in relative motion can be eliminated by transforming the rotor variables to variables associated with fictitious stationary windings. Later, G. Kron proposed a transformation of both stator and rotor variables to a synchronously rotating reference frame that moves with the rotating magnetic field. D. S. Brereton proposed a transformation of stator variables to a rotating reference frame that is fixed on the rotor. In fact, it was shown later by Krause and Thomas that time-varying inductances can be eliminated by referring the stator and rotor variables to a common reference frame which may rotate at any speed.

3.2 AXES TRANSFORMATION

Consider a symmetrical three-phase induction machine with stationary as-bs-cs axes at $2\pi/3$-angle apart, as shown in Fig 2. Our goal is to transform the three-phase stationary reference frame (as-bs -cs) variables into two-phase stationary reference frame (d-q) variables and then transform these to synchronously rotating reference frame (d'-q'), and vice-versa [3, 56]. Assume that the d', q' Axes are oriented at $\theta$ angle, as shown in Fig 2. The voltages
\[ V_{ds}^s \text{ and } V_{qs}^s \text{ can be resolved into as-bs-cs components} \]
\[
\begin{bmatrix}
V_{as}^s \\
V_{bs}^s \\
V_{cs}^s
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta & 1 \\
\cos(\theta - 120^\circ) & \sin(\theta - 120^\circ) & 1 \\
\cos(\theta + 120^\circ) & \sin(\theta + 120^\circ) & 1
\end{bmatrix}
\begin{bmatrix}
V_{qs}^s \\
V_{ds}^s \\
V_{as}^s
\end{bmatrix}
\]
\( (1) \)

The corresponding inverse relation is.
\[
\begin{bmatrix}
V_{qs}^s \\
V_{ds}^s \\
V_{as}^s
\end{bmatrix} =
\frac{2}{3}
\begin{bmatrix}
\cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\
\sin \theta & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ) \\
0.5 & 0.5 & 0.5
\end{bmatrix}
\begin{bmatrix}
V_{as}^s \\
V_{bs}^s \\
V_{cs}^s
\end{bmatrix}
\]
\( (2) \)

Where \( V_{as}^s \) is added as the zero sequence component, which may or may not be present. The current and flux linkages can be transformed by similar equations. It is convenient to set \( \theta = 0 \), so that the q' axis is aligned with the as-axis, the transformation relations can be simplified by ignoring zero sequence. Fig 3 shows the synchronously rotating d'-q' frame, which rotates at synchronous speed \( \omega_s \), with respect to the d'-q' axes and the angle \( \theta_e = \omega_e t \). The two-phase d'-q' windings are transformed into the hypothetical windings mounted on the d'-q' axes [3]. The voltages on the d'-q' axes can be converted (or resolved) into the d'-q' frame as follows:
\[
V_{qs} = V_{qs}^s \cos \theta_e - V_{ds}^s \sin \theta_e 
\]
\( (3) \)
\[
V_{ds} = V_{qs}^s \sin \theta_e + V_{as}^s \cos \theta_e 
\]
\( (4) \)

For convenience, the superscript e has been dropped from now on from the synchronously rotating frame parameters. Again, resolving the rotating frame parameters into a stationary frame, the relations are:
\[
V_{qs} = V_{qs}^s \cos \theta_e + V_{ds} \sin \theta_e 
\]
\( (5) \)
\[
V_{ds} = -V_{qs} \sin \theta_e + V_{ds} \cos \theta_e 
\]
\( (6) \)

The q'-d' components can also be combined into a vector form:
\[
V'_{qs} = V_{qs} - jV_{ds} = (V_{qs}^s \cos \theta_e - V_{ds}^s \sin \theta_e) - j(V_{qs}^s \sin \theta_e + V_{ds}^s \cos \theta_e)
\]
\[
= (V_{qs}^s - jV_{ds}^s)e^{-j\theta_e} = \vec{V} e^{-j\theta_e}
\]
\( (7) \)

Or inversely
\[
\vec{V} = V_{qs}^s - jV_{ds}^s = (V_{qs} - jV_{ds})e^{+j\theta_e}
\]
\( (8) \)

Note that the vector magnitudes in stationary and rotating frames are equal, that is,
\[
|\vec{V}| = \vec{V}_m = \sqrt{V_{qs}^2 + V_{ds}^2}
\]
\( (9) \)

In Equation (7), \( e^{-j\theta} \) is defined as the inverse vector rotator that converts d'-q' variables into d' - q' variables. The vector \( \vec{V} \) and its components projected on rotating and stationary axes are shown in Fig 3. The as-bs-cs variables can also be expressed in vector form. And also:
\[
\vec{V} = V_{qs}^s - jV_{ds}^s
\]
\[
= \left( \frac{2}{3} V_{as} - \frac{1}{3} V_{bs} - \frac{1}{3} V_{cs} \right) - j \left( - \frac{1}{\sqrt{3}} V_{bs} + \frac{1}{\sqrt{3}} V_{cs} \right)
\]
\[
= \frac{2}{3} \left[ V_{as} + aV_{bs} + a^2V_{cs} \right]
\]
\( (10) \)

Where \( a = e^{j\frac{2\pi}{3}} \). The parameters \( a \) and \( a^2 \) can be interpreted as unit vectors. Similar transformations can be made for rotor circuit variables also [3, 8, 17].

3.3. SYNCHRONOUSLY ROTATING REFERENCE FRAME - DYNAMIC MODEL.
in a synchronously rotating \(d\)-q frame. We can write the following stator circuit equations:

\[
V_{qs} = R_s I_{qs} + \frac{d}{dt} \psi_{qs},
\]

(11)

\[
V_{ds} = R_s I_{ds} + \frac{d}{dt} \psi_{ds},
\]

(12)

Where \(\psi_{qs}\) and \(\psi_{ds}\) are q-axis and d-axis stator flux linkages, respectively. When these equations are converted to \(d\)-q frame, the following equations can be written:

\[
V_{qs} = R_s i_{qs} + \frac{d}{dt} \psi_{qs} + \omega_r \psi_{dl},
\]

(13)

\[
V_{ds} = R_s i_{ds} + \frac{d}{dt} \psi_{ds} - \omega_r \psi_{qs},
\]

(14)

If the rotor is not moving, that is, \(\omega_r = 0\), the rotor equations for a doubly fed wound-rotor machine will be similar to Equations (13) - (14):

\[
V_{qr} = R_r i_{qr} + \frac{d}{dt} \psi_{qr} + \omega_r \psi_{dr},
\]

(15)

\[
V_{dr} = R_r i_{dr} + \frac{d}{dt} \psi_{dr} - \omega_r \psi_{qr},
\]

(16)

The rotor actually moves at speed \(\omega_r\), the d-q axes fixed on the rotor move at a speed \(\omega_e - \omega_r\) relative to the synchronously rotating frame. Therefore, rotor equations should be modified as:

\[
V_{qr} = R_r i_{qr} + \frac{d}{dt} \psi_{qr},
\]

(17)

\[
V_{dr} = R_r i_{dr} + \frac{d}{dt} \psi_{dr},
\]

(18)

\[
\psi_{qs} = L_{ts} i_{qs} + L_m (i_{qs} + i_{qr}),
\]

(19)

\[
\psi_{qr} = L_{ts} i_{qr} + L_m (i_{qs} + i_{qr}),
\]

(20)

\[
\psi_{qm} = L_m (i_{qs} + i_{qr}),
\]

(21)

\[
\psi_{ds} = L_{ts} i_{ds} + L_m (i_{qs} + i_{qr}),
\]

(22)

\[
\psi_{dr} = L_{ts} i_{dr} + L_m (i_{qs} + i_{qr}),
\]

(23)

\[
\psi_{dm} = L_m (i_{ds} + i_{dr}),
\]

(24)

Combining the above expressions with Equations (13), (14), (17) and (18), the electrical transient model in terms of voltages and currents can be given in matrix form as

\[
\begin{bmatrix}
V_{qs} \\
V_{ds} \\
V_{qr} \\
V_{dr}
\end{bmatrix} =
\begin{bmatrix}
R_s + S L_s & \omega L_s & S L_m & \omega L_m \\
-\omega L_s & R_s + S L_s & -\omega L_m & S L_m \\
S L_m & (\omega - \omega L_m) & R_s + S L_s & (\omega - \omega L_m) \\
-(\omega - \omega L_m) & S L_m & -(\omega - \omega L_m) & R_s + S L_s
\end{bmatrix}
\begin{bmatrix}
i_{qs} \\
i_{ds} \\
i_{qr} \\
i_{dr}
\end{bmatrix}
\]

(25)

Where \(S\) is Laplace operator. For a cage motor, \(V_{qs} = V_{ds} = 0\). If the speed \(\omega_e\) is considered constant. Then, knowing the inputs \(V_{qp}\), \(V_{al}\) and \(\omega_e\), the currents \(i_{qp}\), \(i_{al}\) and \(i_{es}\) can be solved from Equation (25). If the machine is fed by current source, \(i_{qs}\), \(i_{ds}\) and \(\omega_e\) are independent. Then the dependent variables \(V_{qs}, V_{ds}, i_{qr}\) and \(i_{dr}\) can be solved from Equation (25). The speed \(\omega_e\) in Equation (25) cannot normally be treated as a constant. It can be related to the torques as

\[
T_e = T_L + J \frac{d\omega_m}{dt} = T_L + \frac{2}{P} J \frac{d\omega_e}{dt}
\]

(26)

Where \(T_L\) is load torque, \(J = \text{rotor inertia}\), and \(\omega_m = \text{mechanical speed}\). Often, for compact representation, the machine model and equivalent circuits are expressed in complex form [3]. Multiplying Equation (14) by \(-j\) and adding with Equation (13) gives

\[
V_{qs} - jV_{ds} = R_s (i_{qs} - j i_{ds}) + \frac{d}{dt} (\psi_{qs} - j \psi_{ds}) + j \omega_e (\psi_{qs} - j \psi_{ds})
\]

(27)

\[
V_{qds} = R_s i_{qds} + \frac{d}{dt} \psi_{qds} + j (\omega_e - \omega_r) \psi_{qds}
\]

(28)

Similarly, the rotor equations (17)-(18) can be combined to represent

\[
V_{qdr} = R_r i_{qdr} + \frac{d}{dt} \psi_{qdr} + j (\omega_e - \omega_r) \psi_{qdr}
\]

(29)

Where \(V_{qes} = 0\). Therefore, the steady-state equations can be derived as

\[
V_s = R_s I_s + j \omega_e \psi_s
\]

(30)

\[
0 = \frac{R_r}{S} I_r + j \omega_e \psi_r
\]

(31)

If the parameter \(R_m\) is neglected. We know that

\[
T_e = \frac{3}{2} \left( \frac{P}{2} \right) \left( \omega \sin \delta \right)
\]

(32)

From Equation (32), the torque can be generally expressed in the vector form as

\[
T_e = \frac{3}{2} \left( \frac{P}{2} \right) \left( \psi_{dm} i_{qr} - \psi_{qm} i_{dr} \right)
\]

(33)

Some other torque expressions can be derived easily as follows:
Equations (25), (26), and (37) give the complete model of the electro-mechanical dynamics of an IM in synchronous frame. Fig 4 shows the block diagram of the machine model along with input voltage & output current transformation [2, 8] and resolving variables into dq components. Renewable energy based water supply system is one of the application [57-74]. In irrigation and drinking water supply, mostly we are using induction motors; hence study of control of induction motor is necessary.

4. CONTROL METHODS

Stator flux linkage is estimated by integrating the stator voltages. Torque is estimated as a cross product of estimated stator flux linkage vector and measured motor current vector [75, 76]. The estimated flux magnitude and torque are then compared with their reference values. If either the estimated flux or torque deviates from the reference more than allowed tolerance, the GTO of the variable frequency drive are turned off and on in such a way that the flux and torque will return in their tolerance bands as fast as possible. Thus DTC is one form of the hysteresis or bang-bang control. This control method implies the properties of the control: Torque and flux can be changed very fast by changing the references, The step response has no overshoot, No coordinate transforms are needed, all calculations are done in stationary coordinate system, No separate modulator is needed, the hysteresis control defines the switch control signals directly [3, 75, 76], and There are no PI current controllers. Thus no tuning of the PI is required.

However, by controlling the width of the tolerance bands the average switching frequency can be kept roughly at its reference value [2, 3]. This also keeps the current and torque ripple small. Thus the torque and current ripple are of the same magnitude than with vector controlled drives with the same switching frequency. Due to the hysteresis control the switching process is random by nature. Synchronization to rotating machine is straightforward due to the fast control; just make the torque reference zero and start the inverter [2, 3, 75, 76]. The flux will be identified by the first current pulse. Typically the control algorithm has to be performed with 10 - 30 microseconds or shorter intervals because of the simplicity of the algorithm.

Fig 4. Synchronously rotating frame machine models with input voltage and output current transformations.
The DTC method performs very well even without speed sensors [3]. However, the flux estimation is usually based on the integration of the motor phase voltages [75, 76]. Due to the inevitable errors in the voltage measurement and stator resistance estimate the integrals tend to become erroneous at low speed. Thus it is not possible to control the motor if the output frequency of the variable frequency drive is zero. However, by careful design of the control system it is possible to have the minimum frequency in the range 0.5 Hz to 1 Hz that is enough to make possible to start an IM with full torque from a standstill situation. A reversal of the rotation direction is possible too if the speed is passing through the zero range rapidly enough to prevent excessive flux estimate deviation [77, 78]. If continuous operation at low speeds including zero frequency operation is required, a position sensor can be added to the DTC system [77-79].

4.1 VIEW OF DIRECT TORQUE CONTROL

In principle the DTC method selects one of the six nonzero and two zero voltage vectors of the inverter on the basis of the instantaneous errors in torque and stator flux magnitude [13, 76]. In spite of its simplicity, DTC allows good torque control in both steady and transient state. Its main characteristic is the good performance, obtaining results as good as the classical vector control. Fig. 5. Shows the Block diagram of the IM drive system based on DTC scheme [3, 75, 76]. DTC method still required further research in order to improve the motor’s performance, as well as achieve a better behavior regarding environment compatibility (Electro Magnetic Interference and Energy), that is desired nowadays for all industrial applications.

4.2 CLASSICAL DIRECT TORQUE CONTROL

Classic DTC makes use of hysteresis comparators with torque and stator flux magnitude errors as inputs to decide which stator voltage vector is applied to motor terminals. The complex plane is divided in six sectors, and a switching table is designed to obtain the required vector based on the hysteresis comparators outputs [3, 4]. Due to fast time constants of stator dynamics it is very difficult to keep machine torque between the hysteresis bands. This can do either by increasing the sampling frequency as in, thus increasing switching frequency, commutation losses and computation requirements, or using multilevel converters. The use of hysteresis comparators in classic DTC implementations give rise to variable switching frequency (VSF), which depends on rotor speed, load, sample frequency, etc.; VSF may excite resonant dynamics in the load and hence constitute a serious drawback of DTC.

Generally there are two methods to reduce the torque and flux ripple for the DTC drives. One is multi level inverter; the other is space vector modulation (SVM) [77, 78]. In the first method, the cost and the complexity will be increased, in the second method, the torque ripple and flux ripple can be reduced, however the switch frequency still changes. In the next section a fuzzy approach is given to reduce torque ripple [8]. This goal is achieved by the fuzzy controller which determinates the desired amplitude of torque hysteresis band.

4.3 TORQUE EXPRESSIONS WITH STATOR AND ROTOR FLUXES

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

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

(39)

Where \( \bar{\psi}_s = \psi_{qs} - j \psi_{ds} \) and \( \bar{I}_s = i_{qs} - j i_{ds} \).

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,

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

(40)

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

(41)

From equations 39, 40 and 41:

\[
\bar{T}_e = \frac{3}{2} \left( \frac{P}{2} \right) \frac{L_m}{L_r L_s} \bar{\psi}_r \bar{\psi}_s
\]

(42)

That is, the magnitude torque is

\[
\bar{T}_e = \frac{3}{2} \left( \frac{P}{2} \right) \frac{L_m}{L_r L_s} |\bar{\psi}_r| |\bar{\psi}_s| \sin \gamma
\]

(43)

Where \( \gamma \) is the angle between the fluxes, indicating the 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 $\gamma$ angle is $\Delta \gamma$, the incremental torque $\Delta T_e$ expression is given as

$$\Delta T_e = \frac{3}{2} \left( \frac{P}{2} \right) \frac{L_m}{L_r L_s} \| \bar{\psi}_r + \Delta \bar{\psi}_s \| \sin \Delta \gamma$$ (44)

### 4.4 CONTROL STRATEGY OF DTC

![Block diagram of the IM drive system based on DTC scheme](image)

Fig 6: In principle the DTC method selects one of the six nonzero and two zero voltage

![Inverter voltage vectors and corresponding stator flux variation in time $\Delta t$](image)

Fig 7: Inverter voltage vectors and corresponding stator flux variation in time $\Delta t$

<table>
<thead>
<tr>
<th>Voltage vector</th>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
<th>$V_5$</th>
<th>$V_6$</th>
<th>$V_7$ or $V_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{\psi}_s )</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>0</td>
</tr>
<tr>
<td>( T_e )</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

Table 1: Switching table of inverter voltage vectors.

<table>
<thead>
<tr>
<th>$H_1$</th>
<th>$H_2$</th>
<th>S(1)</th>
<th>S(2)</th>
<th>S(3)</th>
<th>S(4)</th>
<th>S(5)</th>
<th>S(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>V2</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
<td>V6</td>
<td>V1</td>
</tr>
<tr>
<td>0</td>
<td>V0</td>
<td>V7</td>
<td>V0</td>
<td>V7</td>
<td>V0</td>
<td>V7</td>
<td>V0</td>
</tr>
<tr>
<td>-1</td>
<td>V6</td>
<td>V1</td>
<td>V2</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
<td>V6</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
<td>V6</td>
<td>V1</td>
<td>V2</td>
</tr>
<tr>
<td>-1</td>
<td>V5</td>
<td>V6</td>
<td>V1</td>
<td>V2</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
</tr>
</tbody>
</table>

Table 2: Flux and Torque variations due to applied voltage vector in.

Block diagram of the IM drive system based on DTC scheme is shown in Fig 6. The speed control loop and the flux program as a function of speed are shown as usual and will not be discussed. The command stator flux $\hat{\bar{\psi}}_s$ and
torque $T_e^*$ magnitudes are compared with the respective estimated values and the errors are processed through hysteresis-band controllers, as shown [2]. The flux loop controller has two levels of digital output according to the following relations:

$$H_v = 1 \quad \text{for} \quad E_v > +HB_v$$
$$H_v = -1 \quad \text{for} \quad E_v < -HB_v$$

(45)  
(46)

Where $2HB_v$ is total hysteresis-band width controller. The circular trajectory of the command flux vector $\psi_s^*$ with the hysteresis band rotates in an anti-clockwise direction as shown in Fig 7. The actual stator flux $\psi_s$ is constrained within the hysteresis band and it tracks the command flux in a zigzag path. The control trajectory has three levels of digital output, which have the following relations [2]:

$$H_{fe} = 1 \quad \text{for} \quad E_{fe} > +HB_{fe}$$
$$H_{fe} = -1 \quad \text{for} \quad E_{fe} < -HB_{fe}$$

(47)  
(48)

$$H_{fe} = 0 \quad \text{for} \quad -HB_{fe} < E_{fe} < +HB_{fe}$$

(49)

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 $\psi_s$ lies. There are six sectors (each $\pi/3$ angle wide), as in Fig 7(a). The voltage vector table in Fig 8 receives the input signals $H_v$, $H_{fe}$, and $S(k)$ and generates the appropriate control voltage vector (switching states) for the inverter by lookup table, which is shown in Table 1 (the vector sign is deleted) [2, 3]. The inverter voltage vector and a typical $\psi_s$ are shown in Fig 7(b).

Neglecting the stator resistance of the machine, we can write:

$$\psi_s = \frac{d}{dt}(\psi_s)$$

Or

$$\Delta\psi_s = \psi_s \Delta t$$

(50)  
(51)

Which means that $\psi_s$ can be changed incrementally by applying stator voltage $\psi_s$ for time increment $\Delta t$. The flux increment vector corresponding to each of six inverter voltage vectors is shown in Fig 7. The flux in machine is initially established to at zero frequency (dc) along the trajectory OA shown in Figure 7. With the rated flux, the command torque is applied and the $\psi_s^*$ vector starts rotating [2, 3].

Table 1 applies the selected voltage vector, which essentially affects both the torque and flux simultaneously [2, 3]. The flux trajectory segments AB, BC, CD and DE by the respective voltage vectors $\psi_3^*, \psi_4^*, \psi_5^*$, and $\psi_6^*$ are shown in Figure 7(a). The total and incremental torque due to $\Delta\psi_s$ are explained in Fig 7(b). Note that the stator flux vector changes quickly by, but the $\psi_s$ change is very sluggish due to large time constant $T_e$. Since $\psi_s$ is more filtered, it moves uniformly at frequency $\omega$, whereas $\psi_s$ 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 $\psi_s$ shown in Fig 7(b) [2, 3]. The flux can be increased by the $\psi_1^*, \psi_2^*$, and $\psi_3^*$ vectors, whereas it can be decreased by the $\psi_3^*, \psi_4^*$, and $\psi_6^*$ vectors [2]. Similarly, torque is increased by the $\psi_2^*, \psi_3^*$, and $\psi_4^*$ vectors, but decreased by the $\psi_1^*, \psi_5^*$, and $\psi_6^*$ vectors. The zero vectors ($\psi_0$ or $\psi_4$) short-circuit the machine terminals and keep the flux and torque unaltered. Due to finite resistance ($R_s$) drop, the torque and flux will slightly decrease during the short-circuit condition.

Consider for example, an operation in sector S(2) as shown in Fig 7(a), where at point B, the flux is too high and the torque is too low; that is, $H_v = -1$ and $H_{fe} = -1$. From table 1, voltage $\psi_4$ is applied to the inverter, which will generate the trajectory BC. At point C, $H_v = +1$ and $H_{fe} = +1$ and this will generate the $\psi_3$ vector from the table. The drive can easily operate in the four quadrants, and speed loop and field-weakening control can be added, if desired [80]. The torque response of the drive is claimed to be comparable with that of a vector-controlled drive [2].

5. FUZZY APPLICATION

Soft computing techniques can apply for nonlinear system [80-83]. A fuzzy controller is introduced to allow the performance of DTC scheme in terms of flux and torque ripple to be improved [84-87]. The speed regulators are conventional PI controllers (CPI), which requires precise math model of the system and appropriate value of PI constants to achieve high performance drive. Therefore, unexpected change in load conditions or environmental factors would produce overshoot, oscillation of the motor speed, oscillation of the torque, long settling time and causes deterioration of drive performance [84-87].
The selected voltage vector is applied for the entire switching period, and thus allows electromagnetic torque and stator flux to vary for the whole switching period. This causes high torque and flux ripples. To overcome these problems in DTC, two fuzzy controllers are widely analyzed in literature [2, 3]. Those are:

1. Fuzzy PI Controller (FPIC) to achieve precision speed control.
2. Fuzzy Logic Duty Ratio Control (FLDRC) to minimize torque & flux ripple.

When Fuzzy Logic is used for the on-line tuning of the PI controller, it receives scaled values of the speed error and change of speed error. Its output is updating in the PI controller gains based on a set of rules to maintain excellent control performance even in the presence of parameter variation and drive non-linearity [87]. Block diagram of the method with close-loop torque and flux control in stator flux coordinate system is presented in Fig 9. The output of the PI flux and torque controllers can be interpreted as the reference stator voltage components $V_{sx}, V_{sy}$ are the stator flux oriented coordinates ($x - y$). Design of Fuzzy Logic Controller is depend on Selection of input variables, Selection of output variable, Number of fuzzy controllers, Selection of Membership functions and Selection of defuzzification. Here, we had taken two fuzzy controllers for torque and flux, triangular membership and centroid defuzzification.

FPIC does dynamically adjusts the gains $k_p$ and $k_i$ to ensure the stability of system over wide torque-speed range, Swift speed response, Less overshoot and, Extremely small steady state errors.

FLDRC does Minimizes torque & flux ripples effectively, increased efficiency, Low acoustic noise, Operates at a lower switching frequency compared to the existing methods, and Reduces computation burden.
By using these two fuzzy controllers we achieve good speed and torque responses. After outputs of these fuzzy controllers (after defuzzification) we generate \( V_x \) and \( V_y \), again converted this X-Y coordinate components to \( \alpha-\beta \) components. By using this values generate 6 pulses with the help of Space Vector Modulation.

CONCLUSION

The paper has presented a DTC drive with fuzzy controller. This controller determinates the desired amplitude of torque hysteresis band. The main advantage is the improvement of torque and flux ripple characteristics at any speed region; this provides an opportunity for motor operation under minimum switching loss and noise.

The two-fuzzy based DTC-SVM-IMD system, thereby dramatically reducing the torque ripple. A fuzzy controller seems to be a reasonable choice to evaluate the amplitude of torque hysteresis band according to the torque ripple level. Fuzzy-PI Controller to achieve precision speed control and Fuzzy Logic Duty Ratio Control is used to minimize torque & flux ripple. When Fuzzy Logic is used for the on-line tuning of the PI controller, it receives scaled values of the speed error and change of speed error.

REFERENCES


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