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Two Fuzzy Logic Controllers Based DTC-SVM of Induction Motor

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Abstract

Among all control methods for induction motor drives (IMD), Direct Torque Control (DTC) seems to be particularly interesting being independent of machine rotor parameters. In spite of its simplicity, DTC allows good torque control in both steady and transient state. DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. Major drawback of Classical DTC is high torque & flux ripples. The most common solution to this problem is to use Space Vector Modulation (SVM) depends on the reference torque and flux. In this Paper two-fuzzy controller along with the SVM technique is applied to inverter. The proposed two-fuzzy based DTC-SVM-IMD system, thereby dramatically reducing the torque ripple. 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. 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. These advantages allow implementing DTC–SVM-IMD with fuzzy for electric vehicles.

Keywords: Direct Torque Control, Fuzzy Controllers, SVM, and Induction Motor Drive.

1. Introduction

Direct torque control (DTC) is receiving wide attention in the recent literature. The DTC uses the hysteresis band to directly control the flux and torque of the machine. When the stator flux falls outside the hysteresis band, the inverter switching stator is changed so that the flux takes an optimal path toward the desired value [1-7]. The name direct torque control is derived from the fact that on the basis of the errors between the reference and the estimated values of torque and flux it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits. The block diagram of classical DTC-SVM is shown in Fig 1.

The main advantages of DTC are robust and fast torque response, no requirements for coordinate transformation no requirements for PWM pulse generation and current regulators [8-17]. The major disadvantage of the DTC drive is the steady state ripples in torque and flux [18]. The pulsations in flux and torque affect the accuracy of speed estimation. It also results in higher acoustical noise and in harmonic losses. A Torque ripple analysis since none of the inverter switching vectors is able to generate the exact stator voltage required to produce the desired changes in torque and flux, torque and flux ripples compose a real problem in DTC induction motor drive. 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. Due to fast time constants of stator dynamics it is very difficult to keep machine torque between the hysteresis bands. This can be done either by increasing the sampling frequency as in, thus increasing switching frequency, commutation losses and computation requirements, or using multilevel power converters.

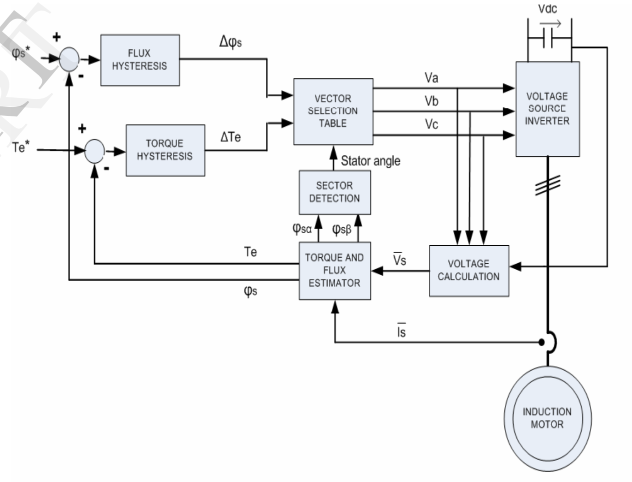


Fig 1. Block diagram of DTC-SVM

The use of hysteresis comparators in classic DTC implementations give rise to variable switching frequency, which depends on rotor speed, load, sample frequency, etc. This variable switching frequency 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) [18- 28]. 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. Most of these methods are computationally intensive. In the next section a fuzzy approach is proposed to reduce torque ripple [18]. This goal is achieved by the fuzzy controller which determinates the desired amplitude of torque hysteresis band.

2. PROPOSED WORK

A fuzzy controller is introduced to allow the performance of DTC scheme in terms of flux and torque ripple to be improved. The speed regulators are conventional PI controllers (CPIC), 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.

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. 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. The proposed DTC-SVM with Fuzzy system is shown in Fig2. Block diagram of the method with close-loop torque and flux control in stator flux coordinate system is presented in Fig. 2. 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.

3. FUZZY PROPOSED APPROACH AND TORQUE RIPPLE MINIMISATION

FPIC does bellow works:

- 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.
- Extremely small steady state errors.

FLDRC does bellow works:

- Minimizes torque & flux ripples effectively
- Increased efficiency.
- Low acoustic noise.
- Operates at a lower switching frequency compared to the existing methods.
- Reduces computation burden.

By using these two fuzzy controllers we achieve good speed and torque responses. After out puts of this fuzzy controllers (after defuzzification) we generate V_{sx} and V_{sy}, again converted this X-Y coordinate components to α-β components. By using this values generate 6 pulses with the help of Space Vector Modulation (this is describes in section IV).

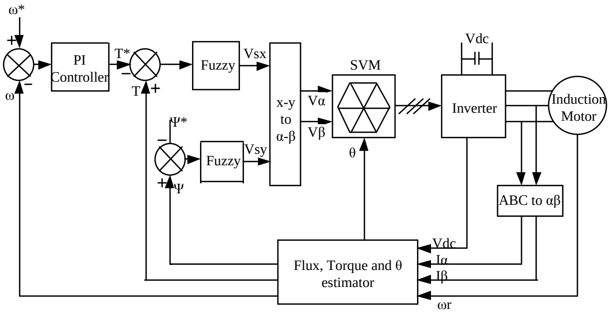


Fig 2: Proposed DTC-SVM model

4. DTC CONTROLLER

DTC is said to be one of the future ways of controlling the Induction Motor (IM) in four quadrants. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state [18, 29-40]. 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 [18, 41-55]. 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 Vector controllers [18, 56-61]. 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 [18, 62-70]. 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 [2, 18, 24].

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 IM. Before going to DTC, first we study about the mathematical background of DTC.

a. Mathematical Model of Induction Motor

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 [71-80]. 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 [18].

b. Dynamic d-q Model of Induction Motor

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.

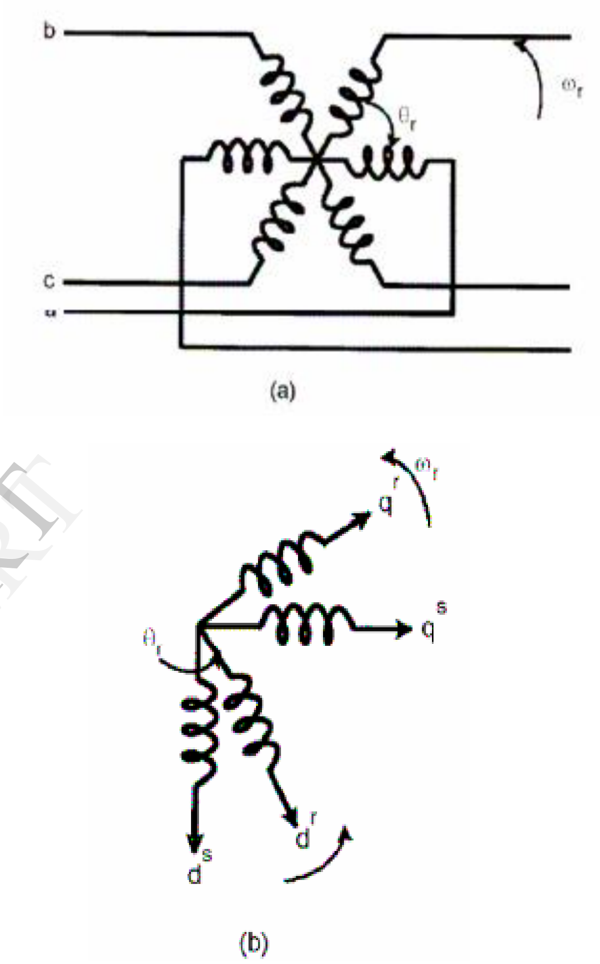


Fig 3: (a) Coupling effect in three-phase stator and rotor windings of motor; (b) Equivalent two-phase machine.

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 3(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 θ_r correspond to rotor direct and quadrature axes [2-4, 7, 18, 81-90]. Note that a three-phase machine can be represented by an equivalent two-phase machine as shown in Fig 3(b), where $d^s \sim q^s$ correspond to stator direct and quadrature axes, and $d^r \sim q^r$ is corresponding to rotor.

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 [18, 90-93]. 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 [2-7]. 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.

c. Axes Transformation

Consider a symmetrical three-phase induction machine with stationary as-bs-cs axes at 2π/3-angle apart, as shown in Fig 4. Our goal is to transform the three-phase stationary reference frame (as-bs - cs) variables into two-phase stationary reference frame ($d^s \sim q^s$) variables and then transform these to synchronously rotating reference frame ($d^e \sim q^e$), and vice-versa [2, 17, 18]. Assume that the $d^e - q^e$. Axes are oriented at θ angle, as shown in Fig 4.

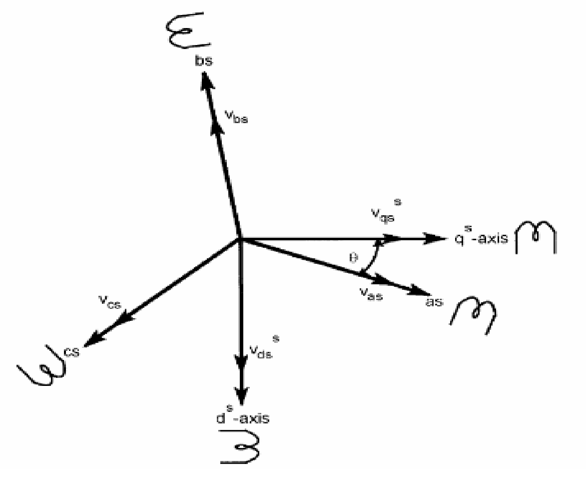


Fig 4. Stationary frame a~b~c to ds~qs axes transformation.

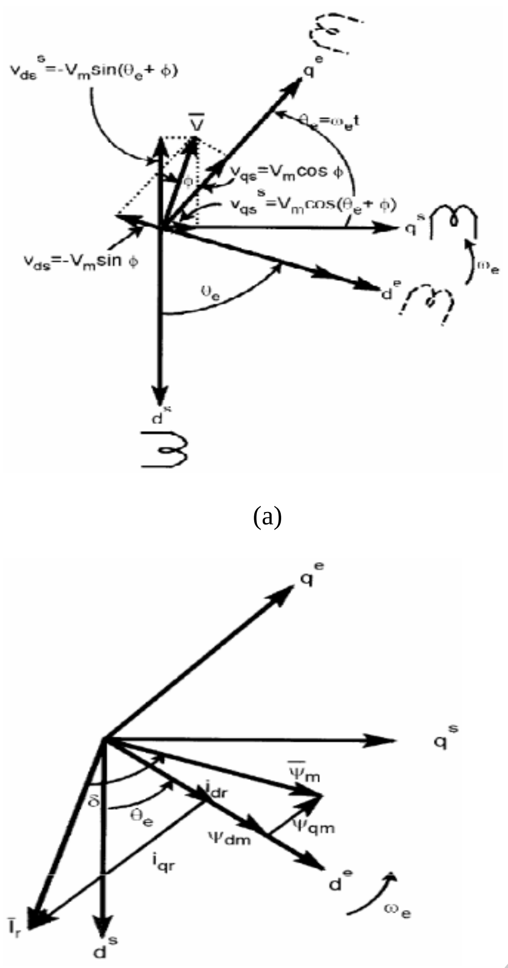
The voltages V_{ds}^s and V_{qs}^s can be resolved into as-bs-cs components and can be represented in the matrix form as

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^0) & \sin(\theta - 120^0) & 1 \\ \cos(\theta + 120^0) & \sin(\theta + 120^0) & 1 \end{bmatrix} \begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{os}^s \end{bmatrix} \quad (1)$$

The corresponding inverse relation is.

$$\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^0) & \cos(\theta + 120^0) \\ \sin\theta & \sin(\theta - 120^0) & \sin(\theta + 120^0) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (2)$$

Where V_{os}^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 θ = 0, so that the q^s axis is aligned with the as-axis, the transformation relations can be simplified by ignoring zero sequence. Fig 5 shows the synchronously rotating d^e- q^e, which rotates at synchronous speed ω_e with respect to the d^s-q^s axes and the angle $\theta_e = \omega_e t$. the two-phase d^e- q^s windings are transformed into the hypothetical windings mounted on the de-qe axes [2].



(a)

(b)

Fig.3: (a) Stationary frame d^s - q^s to rotating frame d^e - q^e ; (b) Flux and current vectors d^e - q^e.

The voltages on the d^s-q^s axes can be converted (or resolved) into the d^e-q^e frame as follows:

$$V_{qs} = V_{qs}^{s}\cos\theta_e - V_{ds}^{s}\sin\theta_e \qquad (3)$$

$$V_{ds} = V_{qs}^{s}\sin\theta_e + V_{ds}^{s}\cos\theta_e \qquad (4)$$

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.

$$V_{qs}^{s} = V_{qs}\cos\theta_e + V_{ds}\sin\theta_e \qquad (5)$$

$$V_{ds}^{s} = -V_{qs}\sin\theta_e + V_{ds}\cos\theta_e \qquad (6)$$

The q^e -d^e components can also be combined into a vector form:

$$V_{qds}^{e} = V_{qs} - jV_{ds} = (V_{qs}^{s}\cos\theta_e - V_{ds}^{s}\sin\theta_e) - j(V_{qs}^{s}\sin\theta_e + V_{ds}^{s}\cos\theta_e)$$
$$= (V_{qs}^{s} - jV_{ds}^{s})e^{-j\theta_e} = \overline{V}e^{-j\theta_e}$$
$$(7)$$

Or inversely

$$\overline{V} = V_{qs}^{s} - jV_{ds}^{s} = (V_{qs} - jV_{ds})e^{+j\theta_e} \qquad (8)$$

Note that the vector magnitudes in stationary and rotating frames are equal, that is,

$$\left|\overline{V}\right| = \hat{V}_m = \sqrt{V_{qs}^{2} + V_{ds}^{2}} \qquad (9)$$

In Equation (7), $e^{-j\theta_e}$ is defined as the inverse vector rotator that converts d^s -q^s variables into d^e -q^e variables. The vector V and its components projected on rotating and stationary axes are shown in Fig 5. The as-bs-cs variables can also be expressed in vector form. And also:

$$\overline{V} = V_{qs}^{s} - jV_{ds}^{s}$$
$$= \left(\frac{2}{3}V_{as} - \frac{1}{3}V_{bs} - \frac{1}{3}V_{cs}\right) - j\left(-\frac{1}{\sqrt{3}}V_{bs} + \frac{1}{\sqrt{3}}V_{cs}\right)$$
$$= \frac{2}{3}\left[V_{as} + aV_{bs} + a^2V_{cs}\right]$$
$$(10)$$

Where a=e j 2∏ / 3. The parameters a and a^2 can be interpreted as unit vectors. Similar transformations can be made for rotor circuit variables also [2, 8, 18].

d. Synchronously Rotating Reference Frame-Dynamic Model

For the two-phase machine shown in Fig 5, we need to represent both d^s -q^s and d^r – q^r circuits and their variables in a synchronously rotating d^e -q^e frame. We can write the following stator circuit equations:

$$V_{qs}^{s} = R_s I_{qs}^{s} + \frac{d}{dt}\psi_{qs}^{s} \qquad (11)$$

$$V_{ds}^{s} = R_s I_{ds}^{s} + \frac{d}{dt}\psi_{ds}^{s} \qquad (12)$$

Where ψ_{qs}^{s} and ψ_{ds}^{s} are q- axis and d-axis stator flux linkages, respectively. When these equations are converted to d^e -q^e frame, the following equations can be written:

$$V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \quad (13)$$

$$V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \quad (14)$$

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):

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_e \psi_{dr} \quad (15)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_e \psi_{qr} \quad (16)$$

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, rotor equations should be modified as.

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \quad (17)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_{r)}\psi_{qr} \quad (18)$$

The de -qe dynamic model equivalent circuits that satisfy Equations (13), (14) and (17), (18). A special advantage of the d^e -q^e dynamic model of the machine is that all the sinusoidal variables in stationary frame appear as dc quantities in synchronous frame. The flux linkage expressions in terms of the currents can be written from Fig 5(b) as follows:

$$\psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \quad (19)$$

$$\psi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \quad (20)$$

$$\psi_{qm} = L_m (i_{qs} + i_{qr}) \quad (21)$$

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \quad (22)$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \quad (23)$$

$$\psi_{dm} = L_m (i_{ds} + i_{dr}) \quad (24)$$

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

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_m & (\omega_e - \omega_r)L_m & R_r + SL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & SL_m & -(\omega_e - \omega_r)L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (25)$$

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

$$T_e = T_L + J\frac{d\omega_m}{dt} = T_L + \frac{2}{P}J\frac{d\omega_r}{dt} \quad (26)$$

Where T_L = load torque, J = rotor inertia, and ω_m = mechanical speed. Often, for compact representation, the machine model and equivalent circuits are expressed in complex form [2]. Multiplying Equation (14) by –j and adding with Equation (13) gives.

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

(27) Or

$$V_{qds} = R_s i_{qds} + \frac{d}{dt}\psi_{qds} + j(\omega_e - \omega_r)\psi_{qds} \quad (28)$$

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

$$V_{qdr} = R_r i_{qdr} + \frac{d}{dt}\psi_{qdr} + j(\omega_e - \omega_r)\psi_{qdr} \quad (29)$$

Where V_{qdr}=0. Therefore, the steady-state equations can be derived as

$$V_s = R_s I_s + j\omega_e \psi_s \quad (30)$$

$$0 = \frac{R_r}{S} I_r + j\omega_e \psi_r \quad (31)$$

If the parameter Rm is neglected. We know that

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\bar{\psi}_m \bar{I}_r \sin\delta \quad (32)$$

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

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\overline{\psi}_m x\bar{I}_r \qquad (33)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\psi_{dm} i_{qr} - \psi_{qm} I_{dr} \qquad (34)$$

Some other torque expressions can be derived easily as follows:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\psi_{dm} i_{qs} - \psi_{qm} I_{ds} \qquad (35)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\psi_{ds} i_{qs} - \psi_{qs} I_{ds} \qquad (36)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)L_m(i_{qs} i_{dr} - i_{ds} i_{qr}) \qquad (37)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{dr} i_{qr} - \psi_{qr} I_{dr}) \qquad (38)$$

Equations (25), (26), and (37) give the complete model of the electro-mechanical dynamics of an IM in synchronous frame. Fig 6 shows the block diagram of the machine model along with input voltage & output current transformation [2, 8] and resolving variables into dqe components.

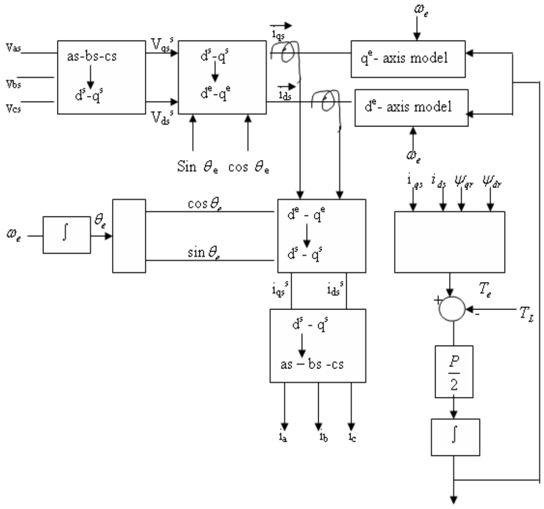


Fig 4. Synchronously rotating frame machine models with input voltage and output current transformations.

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 [18, 19]. 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 [20]. 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, 18, 19], 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 [21-23]. Synchronization to rotating machine is straightforward due to the fast control; just make the torque reference zero and start the inverter [2, 3, 18, 19]. 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.

The DTC method performs very well even without speed sensors [2]. However, the flux estimation is usually based on the integration of the motor phase voltages [18, 19]. 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 [20, 21]. If continuous operation at low speeds including zero frequency operation is required, a position sensor can be added to the DTC system [20-22].

e. 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, 15-19]. 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 7. Shows the Block diagram of the IM drive system based on DTC scheme [2, 18, 19]. 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.

The way to impose the require stator flux is by means of choosing the most suitable Voltage Source Inverter state. If the ohmic drops are neglected for simplicity, then the stator voltage impresses directly the stator flux in accordance with the following equations (39) & (40):

$$\frac{d\overline{\Psi}_s}{dt} = \overline{u}_s \tag{39}$$

Or

$$\Delta\overline{\Psi}_s = \overline{u}_s \Delta t \tag{40}$$

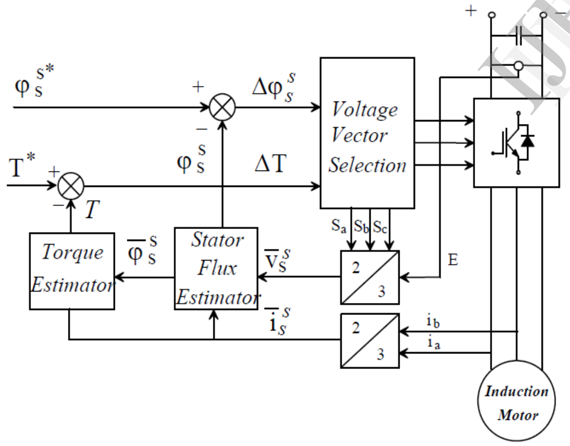


Fig 7: In principle the DTC method selects one of the six nonzero and two zero voltage

Decoupled control of the stator flux modulus and the torque is achieved by acting on the radial and tangential components respectively of the stator flux-linkage space vector in its locus. These two components are directly proportional (Rs =0) to the components of the same voltage space vector in the same directions. Fig 8 shows the possible dynamics locus of the stator flux, and its different variation depending on the VSI states chosen. The possible global locus is divided into six different sectors signaled by the discontinuous line.

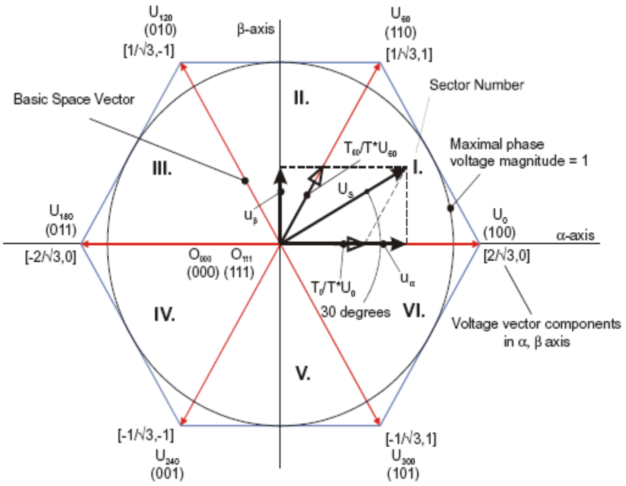


Fig 8: Stator flux vector locus and different possible switching voltage vectors.

In accordance with Fig 8, the general Table 1 can be written. It can be seen from Table 1 that the states Vk and Vk+3, are not considered in the torque because they can both increase (first 30 degrees) or decrease (second 30 degrees) the torque at the same sector depending on the stator flux position.

VOLTAGE VECTOR	INCREASE	DECREASE
Stator Flux	V_k, V_{k+1}, V_{k-1}	V_{k+2}, V_{k-2}, V_{k+3}
Torque	V_{k+1}, V_{k+2}	V_{k-1}, V_{k-2}

Table 1: General Selection Table for Direct Torque Control, being "k" the sector number.

Finally, the DTC classical look up table is as follows:

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
FI	**TI**	**V**	**V**	**V**	**V**	**V**	**V**
	T=	V_2	V_3	V_4	V_5	V_6	V_1
	TD	V_0	V_7	V_0	V_7	V_0	V_7
FD	**TI**	V_3	V_4	V_5	V_6	V_1	V_2
	T=	V_7	V_0	V_7	V_0	V_7	V_0
	TD	V_5	V_6	V_1	V_2	V_3	V_4

Table 2: Look up table for Direct Torque Control.

FD/FI: flux decrease/increase. TD/T/TI: torque decrease/ equal/increase. Sx: stator flux sector. Φ: stator flux modulus error after the hysteresis block. τ: torque error after the hysteresis block.

The sectors of the stator flux space vector are denoted from S1 to S6. Stator flux modulus error after the hysteresis block (Φ) can take just two values. Torque error after the hysteresis block (τ) can take three different values. The zero voltage vectors V0 and V7 are selected when the torque error is within the given hysteresis limits, and must remain unchanged. This is shown in Table 2.

5. RESULTS

In this paper, presents results of torque, speed and flux trajectory of DTC SVM with Two-fuzzy controllers of Induction motor. Fig. 9 shows response of reference and generated Torque. In this Simulink from time 1.0 to 1.3 sec. the reference torque is 5 Nm, from time 1.3 to 1.8sec. The motor reference torque is 8nm and from 1.8 to 2 sec. we applied reference torque is 3Nm. Here generated torque is always follows reference torque, at this time induction motor speed is follow as reference speed (80 rad/s) it is shows in Fig 10. The flux trajectory wave is very smooth curve shows in Fig 11. The data of fuzzy and motor parameters are presented in appendix (Table-4). From the stator flux trajectory, it is appreciated that the flux ripple decreases when fuzzy controller is in use.

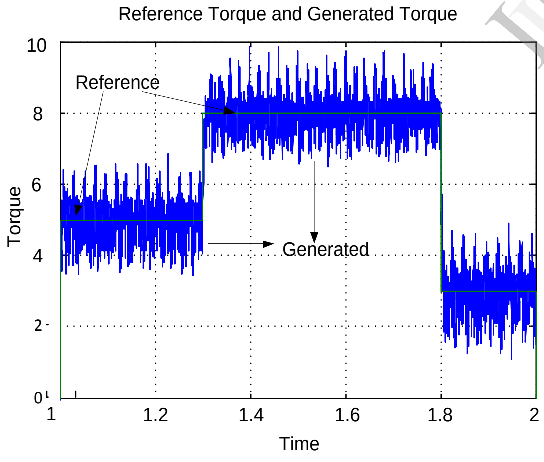


Fig: 9: Reference Torque and Generated Torque.

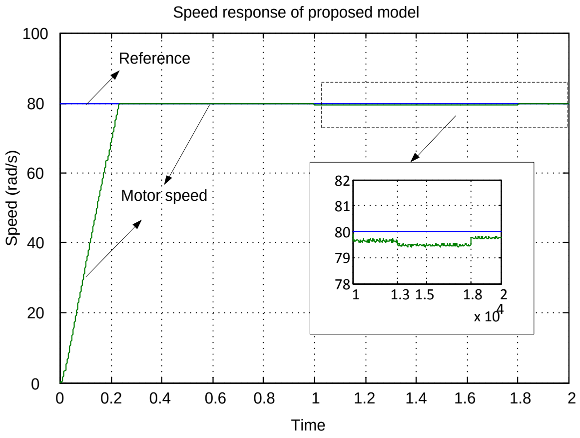


Fig: 10: Reference speed and Generated Speed.

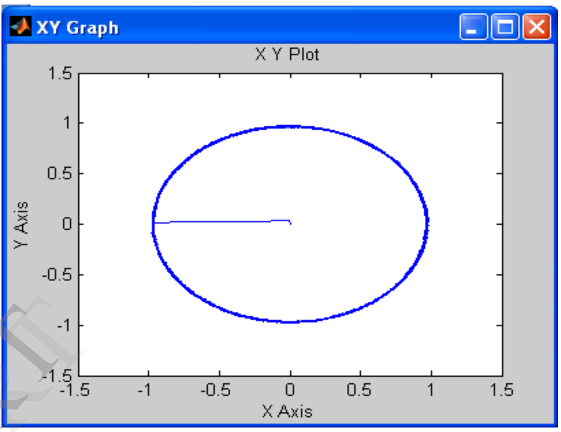


Fig: 11: Stator Flux Trajectory.

6. CONCLUSION

The present paper has presented a DTC drive with fuzzy controller. This controller determinates the desired amplitude of torque hysteresis band. It is shown that the proposed scheme results in improved stator flux and torque responses under steady state condition. 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. These advantages allow implementing DTC–SVM with fuzzy controllers for electric vehicles; because, mainly electric vehicles need high starting torque so this is produce the required torque with minimum torque ripples.

APPENDIX

Fuzzy proposed approach to reduce torque ripple, the fuzzy logic has been proved powerful and able to resolve many problems. A fuzzy controller seems to be a reasonable choice to evaluate the amplitude of torque hysteresis band according to the torque ripple level. In this paper, the amplitude of torque hysteresis band is not prefixed but it is determinate by a fuzzy controller. Based on the analysis given in sections (I, II and III), two inputs are chosen, speed error variation and stator flux variation [18-26]. This is shown in bellow equations (41) and (42).

$$e_1(k) = \overline{\omega}(k) - \overline{\omega}(k-1) \qquad (41)$$

$$e_2(k) = \Psi_s(k) - \Psi_s(k-1) \qquad (42)$$

The magnitude of the stator flux is defined as

$$\Psi_s = \sqrt{(\Psi_{\alpha s}^2 + \Psi_{\beta s}^2)} \qquad (43)$$

From equation (44), the crisp output Δb (incremental amplitude of torque hysteresis band) is integrated in such way that the amplitude of torque hysteresis band is obtained:

$$b_r(k) = b_r(k-1) + \Delta b_r(k-1) \qquad (44)$$

The fuzzy controller design is based on intuition and simulation. For different values of motor speed and current (flux), the values reducing torque and flux ripple were found. These values composed a training set which is used to extract the table rule. The shapes of membership functions are refined trough simulation and testing. The rules sets are shown in Table 2. Figure shows the membership functions of input and output variables. The rules were formulated using analysis data obtained from the simulation of the system using different values of torque hysteresis band. If the amplitude Δb is set too small, the overshoot may touch the upper band which will cause a reverse voltage vector to be selected. This voltage will reduce rapidly the torque causing undershoot in torque response, consequently the torque ripple will remain high. Table3. Fuzzy rules of torque hysteresis controller.

e_1 e_2 Δb_r	NH	NM	NS	ZE	PS	PM	PH
N	N	N	NS	ZE	PS	PS	P
ZE	N	N	NS	ZE	PS	P	P
P	N	NS	NS	ZE	PS	P	P

Table3: fuzzy rules.

PH: positive high, NH: negative high,

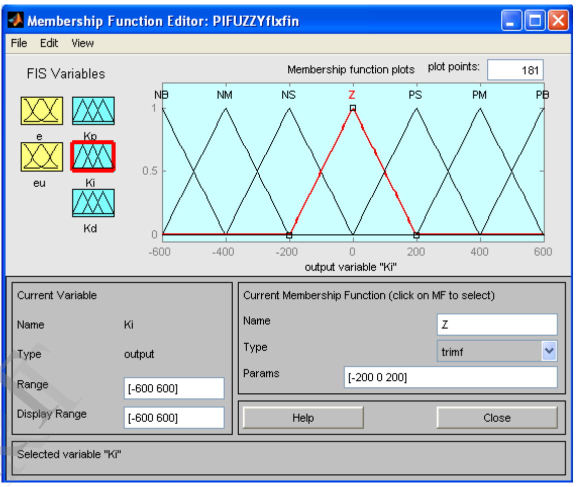
PM: positive medium, NM: negative medium,

PS: positive small, NS: negative small, ZE: zero

Parameters of Induction Motor:

parameter	Value
Stator Resistance (Rs)	7.83 Ω
Rotor Resistance(Rr)	7.55 Ω
Stator Inductance (Ls)	0.4751 H
Rotor Inductance (Lr)	0.4751 H
Mutual Inductance (M)	0.4535 H
Number of poles (p)	4
Inertia (J)	0.07
Friction (B)	0.001
DC Link Voltage (Vdc)	310V

Table:4 parameters of induction motor



plot points: 181

Current Variable
Name Ki
Type output
Range [-600 600]
Display Range [-600 600]

Current Membership Function (click on MF to select)
Name Z
Type trimf
Params [-200 0 200]

Selected variable "Ki"

Fig: A1: KI fuzzy output function of flux fuzzy controller.

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