FUZZY LOGIC METHODOLOGIES FOR TORQUE RIPPLE FREQUENCY REDUCTION IN DIRECT TORQUE CONTROL OF AN INDUCTION MOTOR DRIVE

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ABSTRACT

Direct Torque Control (DTC) is one of the commonly used techniques for speed control of induction motor drive. Among the various control techniques available, DTC is characterized by the absence of coordinate transformations, current regulators and PWM signal generators. Though its design is very simple, it provides good torque control. However, the hysteresis band in DTC introduces ripples in torque and flux. In this paper, a comparison of classical DTC technique, conventional fuzzy logic based DTC and the 12 sector methodology fuzzy logic DTC is carried out based on the output torque ripple frequency. Simulated results using MATLAB/ Simulink show improved performance of fuzzy logic methodologies over the classical DTC technique. In addition, advantages of the 12 sector methodology based fuzzy logic DTC over the conventional fuzzy logic based DTC is brought out in this paper.

Keywords: induction motor, direct torque control, fuzzy logic, twelve sector, space vector, inverter.

Nomenclature

$\overrightarrow{T_e}$	Torque
$\overrightarrow{\Psi_s}$	Stator Flux
$\overrightarrow{I_s}$	Stator Current
$\overrightarrow{\Delta\Psi_s}$	Incremental Stator Flux
$\overrightarrow{\Psi_r}$	Rotor Flux
γ	Flux angle
V_s	Stator Voltage
$\overrightarrow{\Delta T_e}$	Incremental Torque
H_Ψ	Flux Hysteresis Band output
E_Ψ	Flux Error
HB_Ψ	Flux Hysteresis band reference
H_T	Torque Hysteresis Band output
E_T	Torque Error
HB_T	Torque Hysteresis band reference
$\overrightarrow{V_s}$	Voltage vector
δ	Duty Ratio

INTRODUCTION

Commonly used techniques for speed control of induction motor drive are V/F ratio control, Direct Torque Control (DTC) and Vector Control. In the scalar or the V/F ratio control technique, there is no control over the torque or flux of the machine. Torque and Flux control is possible with vector control in induction motor drive. However, vector control is highly computationally complex and hence the DTC technique with less computational complexity along with control of torque and flux is preferred in many applications.

However, the DTC has an inherent disadvantage of increased torque ripple. Some of the torque ripple reduction techniques involve the use of high switching frequencies or the change in inverter topology. The change in inverter topology is carried out to achieve more number of states. The DTC can be implemented in several ways in addition to the classical method. Among these are the application of fuzzy logic controller and a twelve-sector division of flux orientation.

In this paper, a comparison is carried out between the classical, conventional fuzzy logic and twelve-sector fuzzy logic methodology DTCs, based on the torque ripple frequency reduction.

Simulation results obtained show that the torque ripple frequency is reduced by applying fuzzy logic in the conventional six-sector methodology of DTC. The twelve sector fuzzy logic methodology DTC reduces the torque ripple frequency even further compared to the conventional six sector methodology with fuzzy control.

DIRECT TORQUE CONTROL

Direct Torque Control (DTC) technique controls the speed of the induction motor by varying its torque and flux. It is based on the appropriate selection of voltage space vectors for the power converter (in this case, the inverter). The stator flux, the rotor speed and the electromagnetic torque are the control parameters. The switching matrix estimates the stator flux whose inputs are the stator voltage and current, and from this stator flux, the electromagnetic torque is calculated.

The reference stator flux is calculated from an optimized flux algorithm. Torque [1] developed in a three phase induction motor is given by Equation (1).

$$\overrightarrow{T_e} = \frac{3}{2} * \frac{P}{2} * \left(\overrightarrow{\Psi_s} \times \overrightarrow{I_s}\right) \tag{1}$$

Figure-1 shows the phasor diagram of the torque, indicating the $\overrightarrow{\Psi_S}$, $\overrightarrow{\Psi_R}$ and $\overrightarrow{I_S}$ for positive torque developed, where $\overrightarrow{\Psi_S}$ the stator flux is, $\overrightarrow{\Psi_R}$ is the rotor flux, $\overrightarrow{I_S}$ is the stator current and γ is the flux angle.

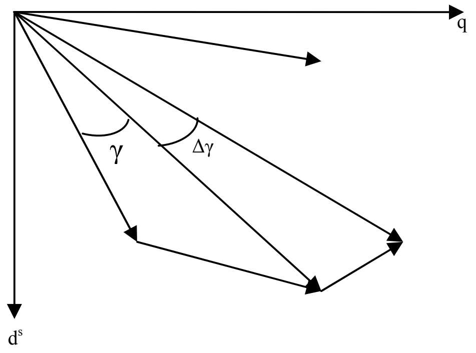


Figure-1. Phasor diagram torque equation

The rotor flux remains constant and the stator flux increases with stator voltage V_s, as shown in Figure-1, with corresponding change of angle γ by $\Delta\gamma$. The incremental torque (ΔT_e) is given by Equation (2).

$$\overline{\Delta T_e} = K * |\overrightarrow{\Psi_R}| \left|\overrightarrow{\Psi_S} + \Delta\overrightarrow{\Psi_S}\right| \sin \Delta\gamma \tag{2}$$

Thus, from the above, it can be concluded that the increase in torque is directly proportional to the change in flux angle. The basic schematic of the classical DTC is shown in Figure-2 [2, 3]. The error in speed is fed to a PI controller to obtain the torque reference. The error in flux is fed to the single band hysteresis controller while the error in torque is fed to the double band hysteresis controller.

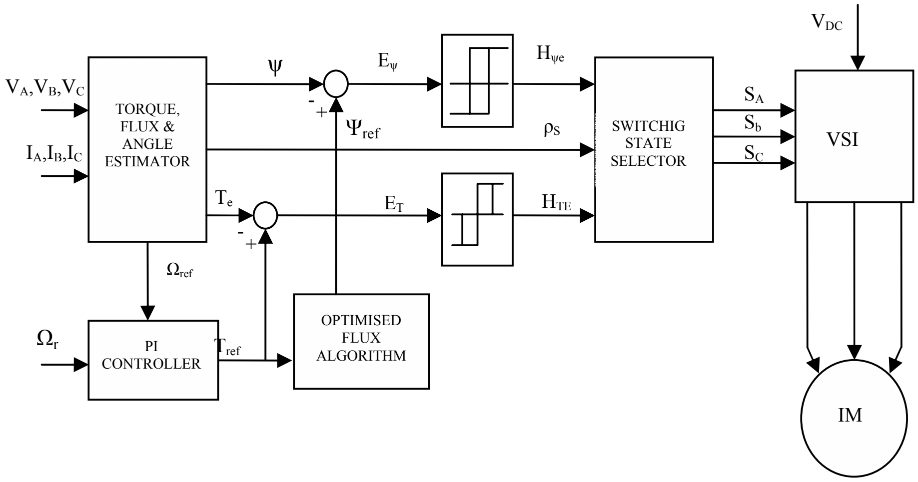


Figure-2. Classical DTC.

Flux hysteresis

The tolerance levels for the flux hysteresis bands [1] are as shown in Equation (3). The locus of the flux reference is a circle, and the flux hysteresis band with a bandwidth of $2HB_\Psi$, rotates as shown in Figure-3. The actual stator flux Ψ_s is constrained within the hysteresis band [4] and tracks the reference flux in a zigzag path [5] as shown in Figure-3. Initially the flux in the machine is established at zero frequency along the trajectory OA.

$$\begin{aligned} H_\Psi &= 1 \text{ for } E_\Psi > +HB_\Psi \\ H_\Psi &= -1 \text{ for } E_\Psi < -HB_\Psi \end{aligned} \tag{3}$$

Torque Hysteresis

The tolerance levels for the torque hysteresis bands are as shown in Equation (4). The double band hysteresis controller for torque control is used to reduce the torque ripple [6]. To decrease the torque, either a zero vector or a corresponding voltage vector that reduces the torque may be applied. When zero vectors are applied, the time taken for the same decrease in torque is more as compared to the case when the corresponding voltage vector is applied, resulting in an increased time for descent.

$$\begin{aligned} H_T &= 1 \text{ for } E_T > +HB_T \\ H_T &= -1 \text{ for } E_T < -HB_T \\ H_T &= 0 \text{ for } +HB_T < E_T < -HB_T \end{aligned} \tag{4}$$

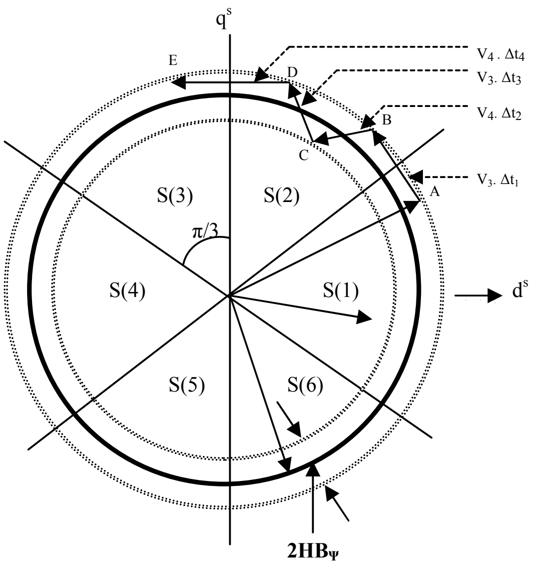
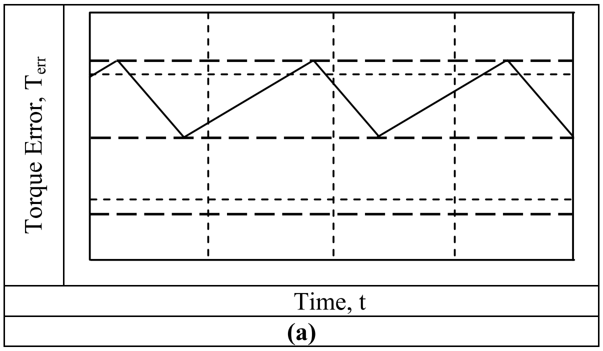
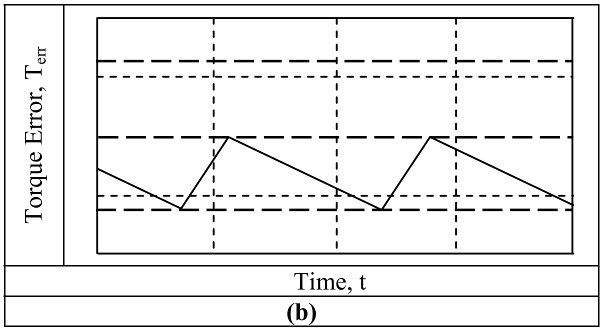


Figure-3. Locus of stator flux.

Hence, in order to reduce the torque ripple, zero vectors are applied instead of the voltage vector [7]. The torque ripple is reduced, as the magnitude of the slope of the torque error when zero vectors are applied is lesser than the magnitude of the slope of the torque error when the voltage space vector that reduces the torque is applied. Hence, in order to apply zero vectors, another level is introduced in-between the two extremes of the hysteresis band so that when the error in torque touches this level; the zero vectors is applied, thus not allowing the torque error to go beyond this level. This phenomenon is depicted in Figure-4. For forward rotation, the reference torque is positive and the error in torque is in the upper band and for reverse rotation, the reference torque is negative and the error in torque is in the lower band. Figure-4 shows the hysteresis band for the error in torque for forward and reverse rotation. The sector in which the flux vector Ψ_S lies is computed. There are six sectors each 60° wide as indicated in Figure-5. The outputs from the hysteresis band controllers and sector information of flux are given to a three-dimensional lookup Table for the selection of the voltage vectors for the control of torque and flux of the machine.



(a)



(b)

Figure-4. Two level torque hysteresis (a) Forward rotation (b) Reverse rotation.

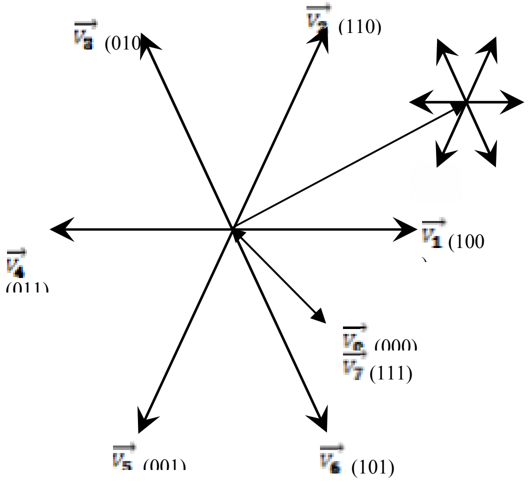


Figure-5. Inverter voltage vectors and corresponding variation in flux.

The voltage vector applied causes a change in the rate of change of flux of the machine, as given in Equations (5) and (6).

$$\vec{V_s} = \frac{d}{dt\left(\vec{\Psi_s}\right)} \tag{5}$$

$$\Delta\vec{\Psi_s} = \vec{V_s} . \Delta t \tag{6}$$

From Equation (6), it can be seen that $\vec{\Psi_s}$ can be incrementally changed by applying the vector $\vec{V_s}$ for an incremental time Δt . Hence the flux trajectory segments AB, BC, CD, and DE of Figure-3 are due to the voltage vectors $\vec{V_3}$, $\vec{V_4}$, $\vec{V_3}$ and $\vec{V_4}$, respectively.

Formation of switching table

Consider, for example, the stator flux is in sector 1. If vectors $V_2$and V_6 are applied, there is an increase in flux. However, V_2 would result in an increase in torque while V_6would result in a decrease in torque. Similarly, application of vectors V_3 and V_5 would result in a decrease in flux. However, V_3 would result in an increase in torque while V_5 would result in a decrease in torque. Considering the flux to be in sector 1, there are four possible conditions, namely:

a) Increase in flux and increase in torque,
b) Increase in flux and decrease in torque,
c) Decrease in flux and increase in torque,
d) Decrease in flux and decrease in torque.

The corresponding vectors to be applied for the above mentioned conditions would be:

a) V2; b) V6; c) V3; d) V5

Proceeding in the same way, the vector selection, shown in Table-1, is formed for various sectors.

Table-1. Voltage vector selection.

H_Ψ	1			-1		
H_{Te}	1	0	-1	1	0	-1
S(1)	V_2	V	V_6	V_3	V_7	V_5
S(2)	V_3	V_7	V_1	V_4	V_0	V_6
S(3)	V_4	V_0	V_2	V_5	V_7	V_1
S(4)	V_5	V_7	V_3	V_6	V_0	V_2
S(5)	V_6	V_0	V_4	V_1	V_7	V_3
S(6)	V_1	V_7	V_5	V_2	V_0	V_4

Need for duty ratio controller

In order to reduce the torque ripple, a double band hysteresis loop is used. However, in this double band hysteresis controller the magnitude of the slope of the torque error when voltage vector is applied is greater than the magnitude of slope of the torque error when zero vectors are applied [7]. If the slope of magnitude of the torque error when voltage vector is applied is reduced, then the torque ripple is reduced further. This is the aim of using the duty ratio controller. The above idea of varying the duty cycle of the voltage vector is shown in Figure-7.

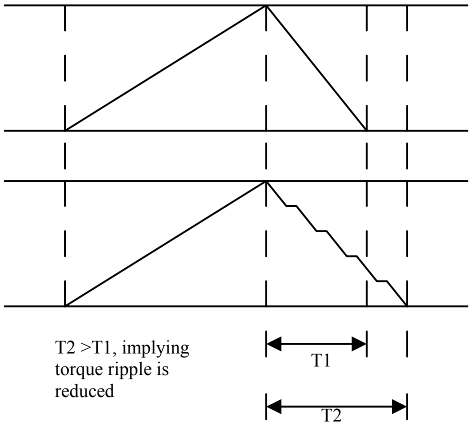


Figure-7. Effect of zero vectors on duty cycle.

The principle of varying the duty cycle [8] can be seen in Figure-8.

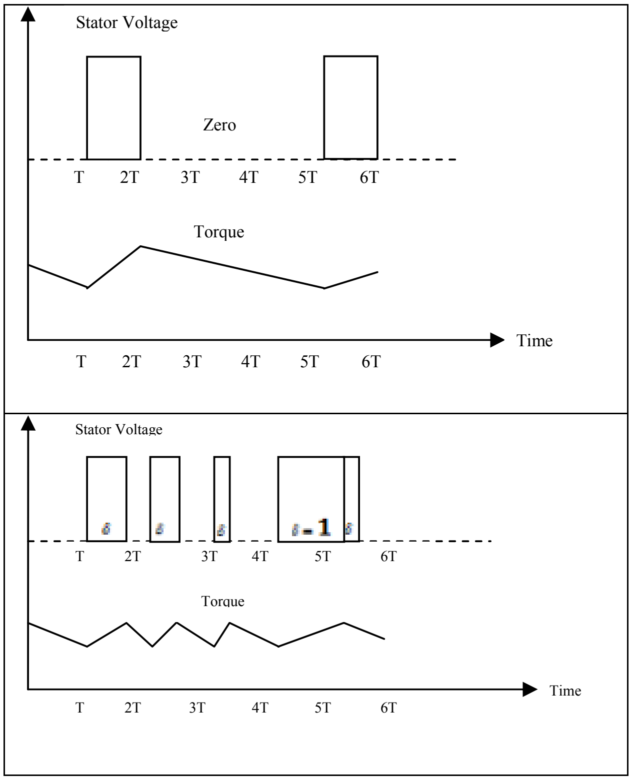


Figure-8. Duty cycle variation.

In the duty ratio control, the voltage vector is applied for a time, which is lesser than the actual time and the zero vector is applied for the remaining time. By controlling the duty ratio of the voltage vector, the torque ripple is reduced.

TWELVE SECTOR METHODOLOGY

In the classical DTC technique, for every sector two vectors (secondary vectors) are not utilized as these vectors have different effects at various positions of the flux vector inside the same sector. Hence in order to use these secondary vectors, the number of flux sectors is 12 instead of the 6 as in the case of the classical DTC.

Now there are four conditions to be satisfied within each sector, among which two conditions can be implemented using the primary or secondary vectors and the remaining two conditions can be implemented only using primary vectors. The flux sector allocation is shown in Figure-9. Considering the flux to be in sector 1, there are four possible conditions, namely:

a) Increase in flux and increase in torque,
b) Increase in flux and decrease in torque,
c) Decrease in flux and increase in torque,
d) Decrease in flux and decrease in torque.

The corresponding vectors to be applied for the above mentioned conditions would be:

a) V2; b) V6, V1; c) V3, V4; d) V5

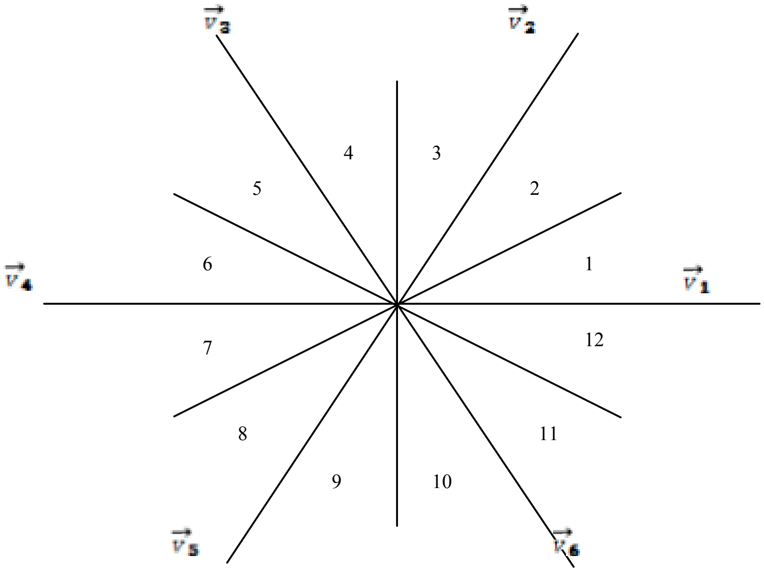


Figure-9. Twelve sector division.

Table-2. Voltage vector selection (12 Sector).

Sector	**Increase in torque**				**Decrease in torque**			
	Increase in flux		**Decrease in flux**		**Increase in flux**		**Decrease in flux**	
1	V2	-	V3	V4	V6	V1	V5	-
2	V3	V2	V4	-	V1	-	V6	V5
3	V3	-	V4	V5	V1	V2	V6	-
4	V4	V3	V5	-	V2	-	V1	V6
5	V4	-	V5	V6	V2	V3	V1	-
6	V5	V4	V6	-	V3	-	V2	V1
7	V5	-	V6	V1	V3	V4	V2	-
8	V6	V5	V1	-	V4	-	V3	V2
9	V6	-	V1	V2	V4	V5	V3	-
10	V1	V6	V2	-	V5	-	V4	V3
11	V1	-	V2	V3	V5	V6	V4	-
12	V2	V1	V3	-	V6	-	V5	V4

Fuzzy logic based DTC

Fuzzy logic is used for the control of non-linear systems. Since the duty ratio for each switching state is a nonlinear function of a number of factors namely torque error, flux error and flux position, it is difficult to represent mathematically the relation between the three variables. Fuzzy logic control seems to be a reasonable choice to determine the duty ratio during each switching state [2]. The schematic of direct torque control with a fuzzy duty ratio control for the six sector based method is shown in Figure-10 while The schematic of direct torque control with fuzzy duty ratio control for the twelve sector based method is shown in Figure-11.

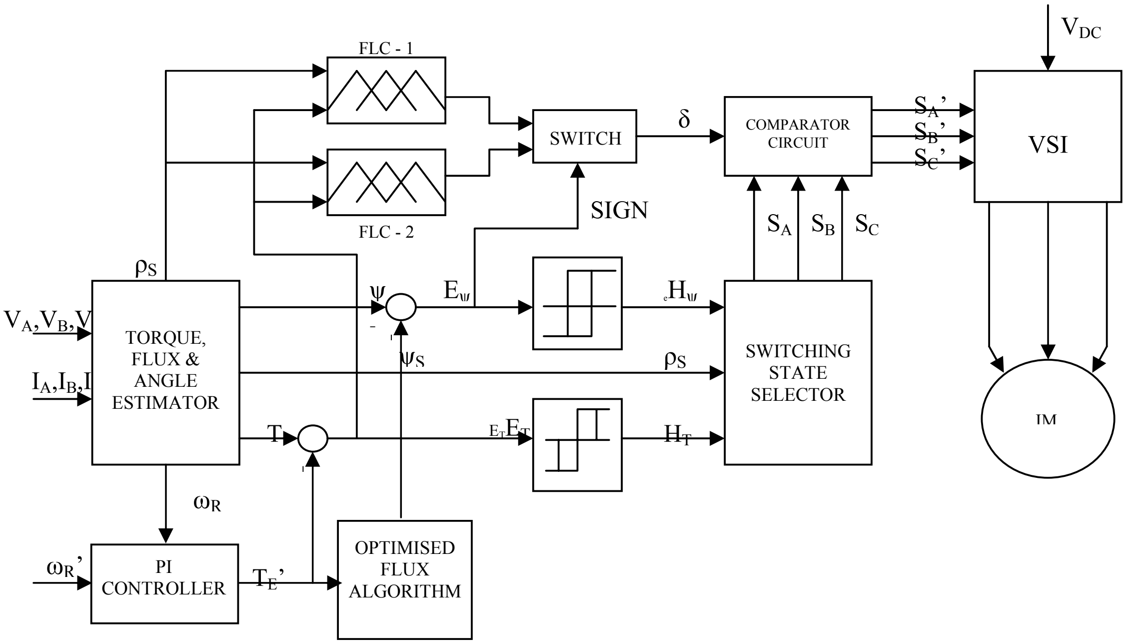


Figure-10. DTC with fuzzy (six sector).

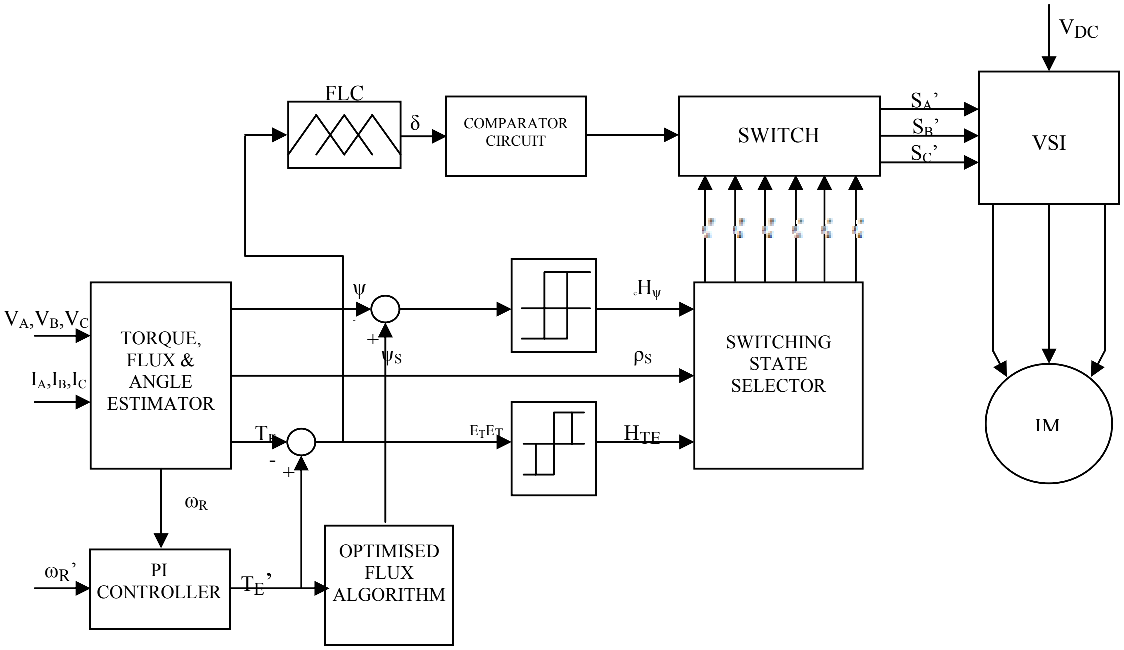


Figure-11. DTC with fuzzy (twelve sector).

In general, a fuzzy logic controller consist of three main parts: fuzzification, fuzzy reasoning (based on fuzzy rules), and defuzzification.

Fuzzification

The torque error, flux error and stator flux angle are given as input variables to the fuzzy controller and the output variable is duty ratio (δ) [7]. Membership functions for the input and output variables for the six sector based DTC are shown in Figure-12. The linguistic variables used are given in Table-3.

Table-3. Linguistic variables (6 sector).

Torque error	
Linguistic variable	**Symbol**
Small	S
Medium	M
Large	L
Duty cycle	
Linguistic variable	**Symbol**
Very small	VS
Small	S
Large	L
Very large	VL
Flux angle	
Linguistic variable	**Symbol**
Very small	VS
Small	S
Large	L
Very large	VL

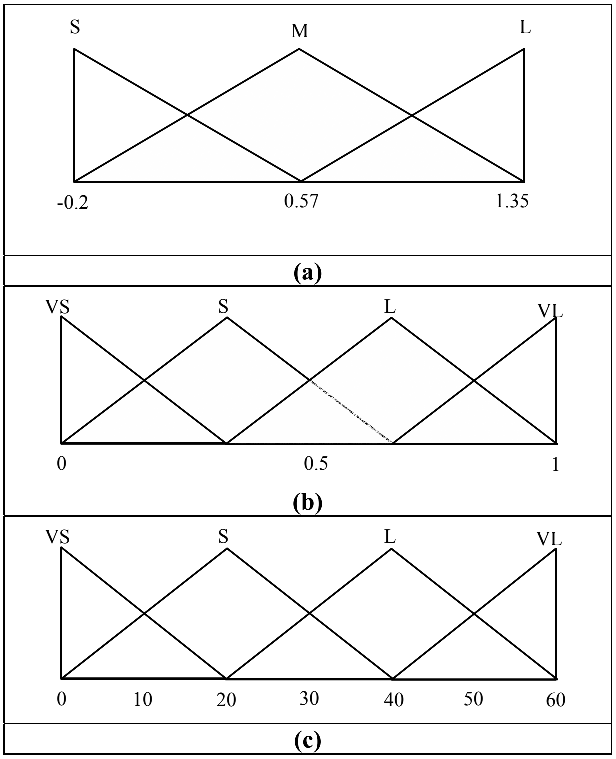


Figure-12. Membership functions of (a) Torque error (b) Duty cycle (c) Flux angle.

Membership functions for input and output variables for the twelve sector based DTC are shown in Figure-13. The linguistic variables used are given in Table-4.

Table-4. Linguistic variable (12 sector).

Torque error	
Linguistic variable	**Symbol**
Small	S
Medium	M
Large	L
Duty cycle	
Linguistic variable	**Symbol**
Small	S
Medium	M
Large	L

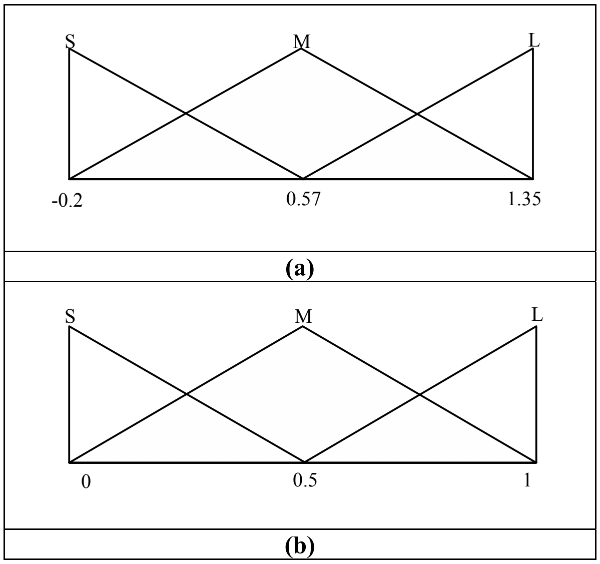


Figure-13. Membership functions for (a) Torque error (b) Duty ratio.

Formation of fuzzy rules

The factors to be considered for framing fuzzy rules are flux error, torque error and flux angle. Let us consider two cases of flux positions in the first sector, say position A and position B as shown in Figure-14. Position A has a small flux angle and position B has a large flux angle. If vector V2 is applied then the increase in angle for the flux at position A is more than that of B. As the increase in flux angle at position A is more, the increase in torque is more. The increase in flux angle at position B is comparatively less and the increase in torque is also comparatively lesser than the increase in torque at position A. So for achieving same increase in torque, the duty cycle for the vector when flux angle is small, should be small and when the flux angle is large then duty cycle should be large [9]. This is the basic criterion for the development of fuzzy rules.

When the torque error is large it is not apt to have a small duty cycle since achieving zero error is more important. So the duty cycle should be made medium rather than small. Let us consider the flux is in sector 1 (current sector) and the torque error is large. If the flux angle is very small then duty cycle should be small. However we can't afford to have a small duty cycle as approaching zero error is more important, so duty cycle is made medium. If the flux angle is small the duty cycle is medium. If the flux angle is large and very large then duty cycle is large as discussed earlier. So from the above discussion the fuzzy rule Table for the six sector methodology is formed as shown in Table-5.

Table-5. Fuzzy rule Table.

Increase in flux				
θ / T_e	**VS**	**S**	**L**	**VL**
S	S	S	M	M
M	S	M	M	L
L	M	M	L	L
Decrease in flux				
θ / T_e	**VS**	**S**	**L**	**VL**
S	M	M	S	S
M	L	M	M	S
L	L	L	M	M

For the twelve sector methodology, fuzzy rules are framed based on the torque error. If the torque error is large then the vector for which the change in torque is more is applied for longer time, so the duty cycle is large [10, 11]. Similarly, if the torque error is small then the vector for which the change in torque is less is applied for a longer time so the duty cycle is small [12] as the duty cycle is the time for which the vector whose change in torque is more.

Consider that the flux is in first sector, in which case, vectors V6 and V1 are applied for increasing the flux and decreasing the torque withV6 as the primary vector and V1 as the secondary vector.

The influence of vectors V6 and V1 result in an increase in flux and decrease in torque; however, the extent to which these two vectors cause the change differs. To achieve a greater decrease in torque, the primary vector V6 can be utilized, and to achieve a comparatively lesser decrease in torque, the secondary vector V1 can be utilized. The time period for which these two vectors are applied, is based on the duty ratio value. Now these two vectors are applied alternatively in order to reduce the torque ripple. The above idea is depicted in the Figure-15.

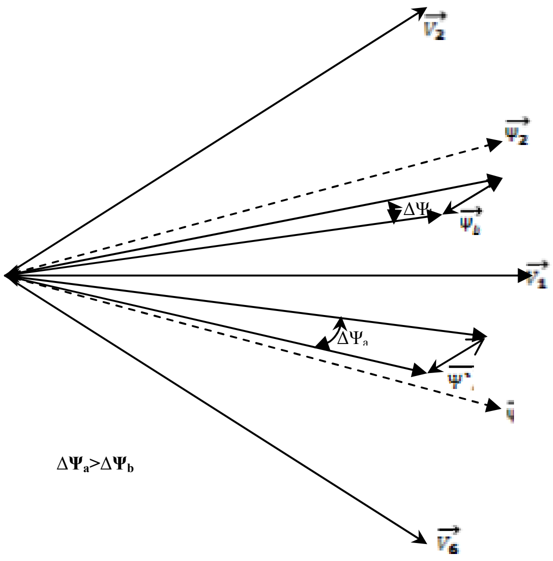


Figure-14. Fuzziness in the system.

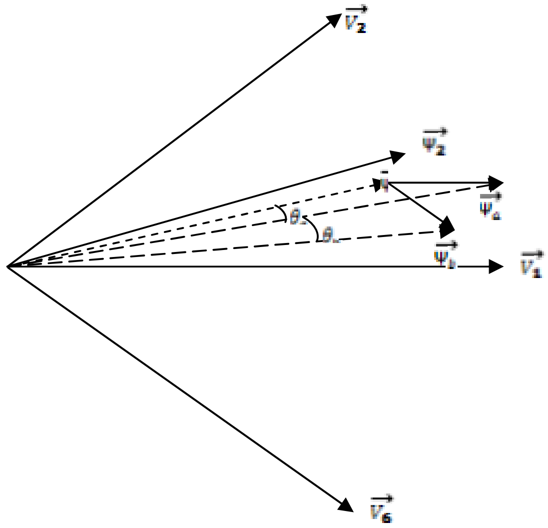


Figure-15. Impact of primary and secondary vectors on flux.

From the above discussion, the fuzzy rule Table for the six sector methodology is formed as shown in Table-6.

Table-6. Fuzzy rule table.

T_e	**S**	**M**	**L**
Duty ratio	S	M	L

Defuzzification

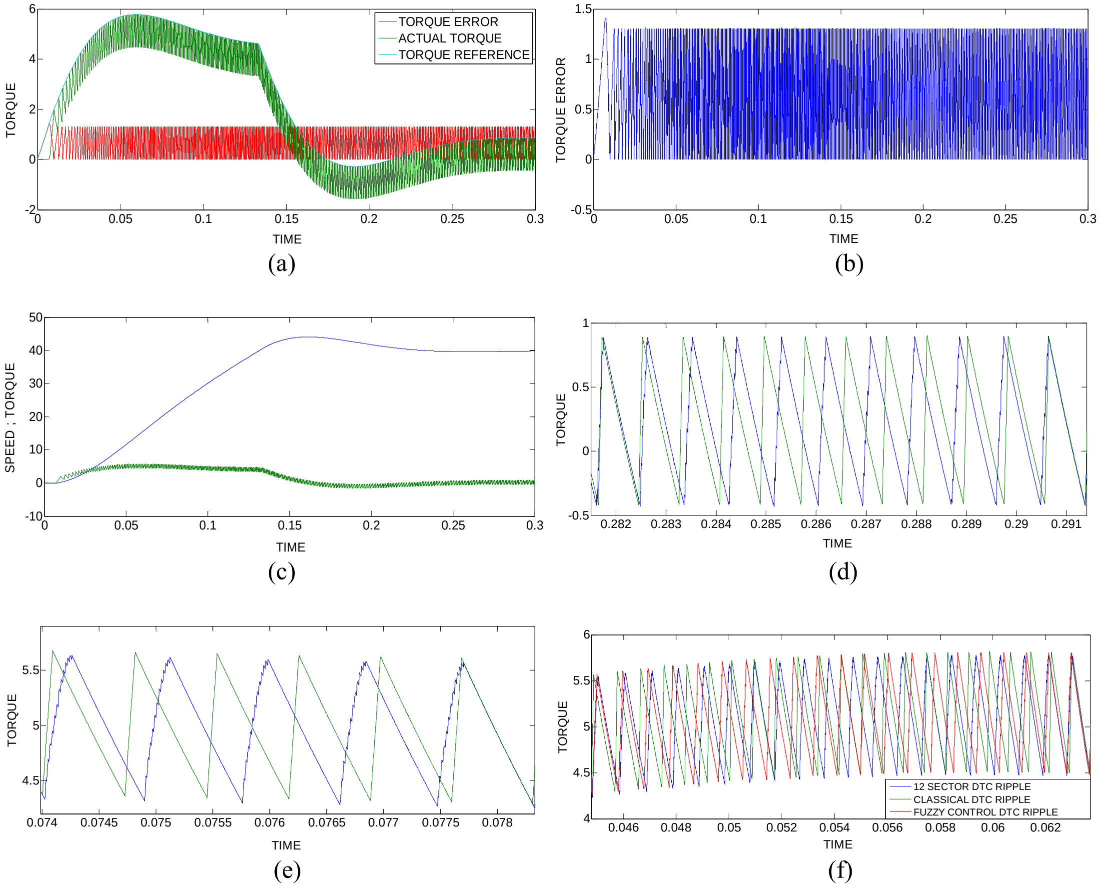
To obtain the output of the fuzzy controller, center of area (COA) defuzzification technique is used. Using this method, the crisp output, δ, is the center of area for the membership function of the overall implied fuzzy action. For continuous output of the universe of discourse, the center of area output is denoted by Equation (7).

$$\delta = \frac{\int \delta . \mu_B(\delta) d\delta}{\int \mu_B(\delta) d\delta} \qquad (7)$$

SIMULATION RESULTS

The Simulink model for DTC of induction motor drive with fuzzy based duty ratio controller is implemented using the MATLAB/ Simulink.

Figure-16(a) shows the torque responses, Figure-16(b) shows the torque error and Figure-16(c) shows the speed-torque responses of the DTC system. The responses shown by the classical DTC, conventional six sector methodology based DTC and the twelve sector methodology based DTC are similar. Figure-16(d) shows the torque ripple comparison between the conventional six sector fuzzy logic based DTC and the classical DTC. Figure-16(e) shows the torque ripple comparison between the twelve sector fuzzy logic based DTC and the classical DTC. Figure-16(f) shows the torque ripple comparison between the twelve sector fuzzy logic based DTC, the conventional six sector fuzzy logic based DTC and the classical DTC.



(a) (b)

(c) (d)

(e) (f)

Figure-16. Response of systems with and without fuzzy logic.

a) Torque responses; b) Torque error ; c) Speed-Torque response ; d) Torque ripple frequency comparison - conventional six sector fuzzy and classical; e) Torque ripple frequency comparison- twelve sector and classical ; f) Torque ripple frequency comparison - twelve sector, fuzzy and classical

From simulation results, it can be seen that the torque ripple frequency is about 1216.93 Hz for the classical DTC scheme. However, the frequency reduces to 1111.11 Hz for the conventional fuzzy logic based DTC. Thus a reduction of 8.69% in the torque ripple frequency is achieved. With the application of the 12 sector fuzzy logic based DTC, the torque ripple frequency further reduces to 1058.20 Hz. Hence, there is a 13.04% reduction in the torque ripple frequency in this technique as compared to the classical DTC. Therefore, it is observed that the conventional DTC reduces the torque ripple frequency as compared to that of the classical DTC, but it is reduced further with the application of the 12 sector methodology.

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The parameters of the induction motor used in this paper are given in Table-7.

Table-7. Motor Specifications.

Rated voltage	400 V
Poles	4
Rated speed	1430 RPM
Stator resistance	1.405 Ω
Rotor resistance	1.395 Ω
Stator leakage inductance	0.005839 H
Rotor leakage inductance	0.005839 H
Mutual inductance	0.1722 H
Moment of inertia	0.0131 J

CONCLUSIONS

In this paper, the classical DTC technique is discussed and its extension with the application of fuzzy logic has also been dealt with. However the fuzzy logic based DTC technique has been broadly talked about by considering the conventional six sector division and the twelve sector division of the stator flux space vector orientation. Based on the torque ripple frequency criteria, it has been shown from simulation results that the frequency is the least for the twelve sector based fuzzy logic DTC and the greatest for the classical DTC, among the three methods. Hence, it is advantageous to use fuzzy logic DTC rather than the conventional DTC. In addition, twelve sector methodology fuzzy DTC has superior performance over six sector methodology fuzzy DTC.

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