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# Direct Torque Control of Induction Motor-A Comparison

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**ABSTRACT**

This paper presents the model of direct torque and flux control of an induction motor drive (IMD) with PI replaced by Fuzzy logic controller (FLC). Direct torque control (DTC) of an induction motor drive is an excellent method to control the flux and torque of an induction motor to settle at a zone. But the major drawback of the DTC is that the torque ripple is high. The major area of research under DTC is to reduce the ripple of torque using various methods such as using 12 sectors, using fuzzy controller, using Artificial neural networks algorithm, using genetic algorithm, etc… In this paper a fuzzy logic model is proposed that had replaced PI where fuzzy completely focuses on reducing the ripple in torque. Here both such models (classical as well as fuzzy) models are simulated using MATLAB/ SIMULINK and the results are compared. The proposed technique had shown better results than compared to the classical model.

**Keywords:** *Direct torque control(DTC), Fuzzy logic control(FLC), PI controller, Induction motor drive(IMD).*

## 1. INTRODUCTION

In general, the setup that controls the speed of rotation of an induction motor is known as a drive. The usage of drives is increasing day by day because of its simple construction and wider range of applications. If there exists a drive system there must also be an existence for control logic, if the drive is connected to an induction motor. There are basically two kinds of control logics known as 1) Scalar control and 2)Vector control. V/f control comes under scalar control where voltage and frequency will have a constant relationship between them. This method is simple in construction due to open loop, so due to this the controllers speed and torque responses are not accurate, where stator flux and torque are not directly controlled. Vector control includes Field oriented control (FOC) and Direct torque control (DTC). Out of these methods Direct torque control method which was proposed by Isao Takahashi and Toshihiko Noguchi, in the mid 1980's[2] is chosen as best one because of its lesser dependency on machine parameters[6], simple implementation and quicker dynamic torque response. DTC of IMD is a method that makes the torque and flux settle at the reference zone and is a closed loop control. Even though there are such a wide range of benefits with the DTC, there are certain drawbacks, among them the main drawback is that the torque ripple is higher. This ripple can be minimized using Fuzzy Logic Control (FLC). Fuzzy is basically human way of depiction of an issue. Fuzzy adapted DTC has few advantages such as low steady state error, robustness, capability of fast tracking and reduces the ripple content [6].

## 2. METHODOLOGY AND BLOCK DIAGRAM

The concept of DTC of IMD is to individually control the torque and the stator flux. This can be obtained by changing the switching states of the inverter that are obtained from the flux and torque hysteresis comparator outputs and by appropriate state selection from the switching table.

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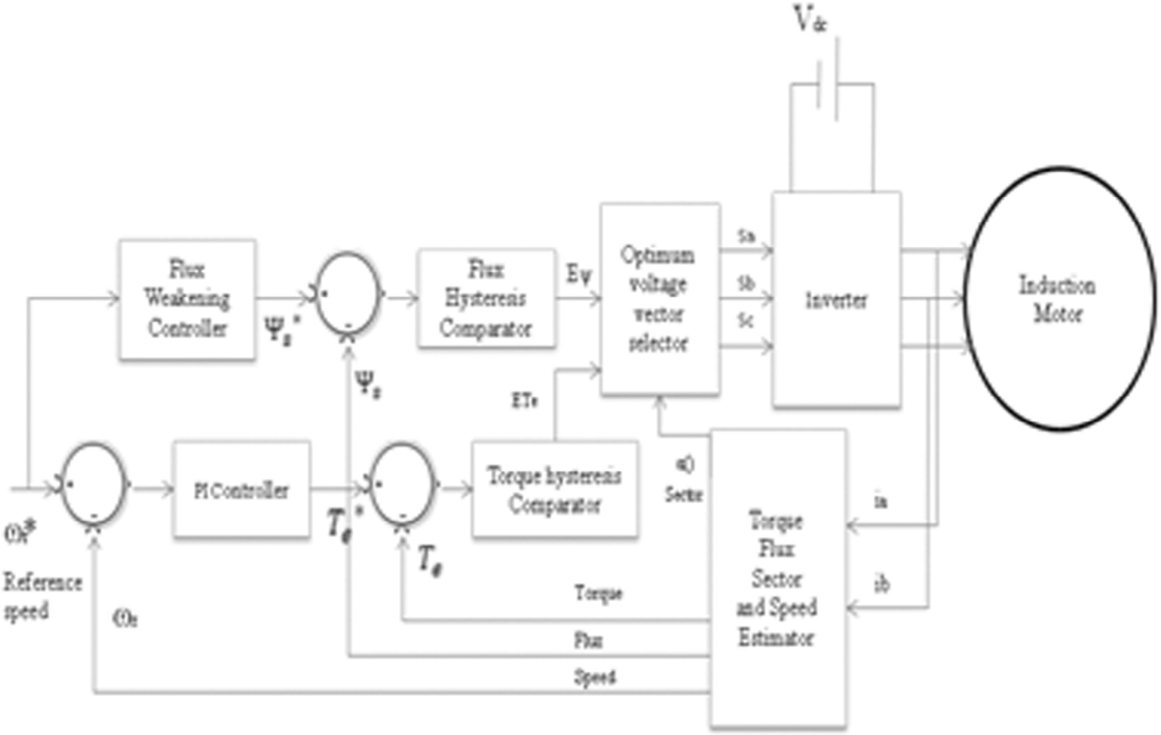


**Figure 1: Block diagram of direct torque control**

Currents ia, ib are taken from the motors as a feedback and are fed to the torque flux and speed estimator block, this block converts these currents into torque and flux parameters which are then compared with the reference torque and reference flux values. The error obtained when reference speed is compared with the current speed, which is fed to a PI controller providing the reference torque. The difference between the reference torque and actual torque as well as the difference between the reference flux and actual flux is fed to the hysteresis controllers (two level for flux and three level for torque), two level hysteresis comparator gives the output as either 0 or 1 and three level gives the output as 0, 1 or -1 which significally says 1 is to increase, 0 is to remain the same, -1 is to decrease. So based on various combinations of these values a switching table as shown in table1 is formed and an appropriate inverter state is selected based on which sector it is present. (The entire space is divided into six sectors).

### 2.1. PI and field weakening controllers

The reference torque Te* is obtained as the output from the PI controller by amplifying the error in speed. The flux weakening controller plays active role only if the machine is made run above the rated speed. So below the rated speed the reference flux is taken as constant value and above the rated speed the stator flux is considered as

$$\psi_s^* = \psi_c.\left(\frac{b}{r}\right)[10] \tag{1}$$

Where ψc is constant flux or the rated flux of the machine and ψs* is the reference flux in case if the speed is above rated speed. ab is the base speed and ar is the rotor speed.

Now the reference flux and the torque obtained from the PI controller are compared with the actual flux and torque and the errors in them are fed to hysteresis comparators.

In this model a three level hysteresis comparator is used for torque and a two level is used for flux and the hysteresis comparators are modeled as shown below.

$$\begin{aligned} H_{\Psi} &= 1 \text{ for } E_{\Psi} > +HB_{\Psi} \\ H_{\Psi} &= 1 \text{ for } E_{\Psi} < -HB_{\Psi} \\ H_{Te} &= 1 \text{ for } E_{Te} > +HB_{T} \\ H_{Te} &= -1 \text{ for } E_{Te} < -HB_{T} \\ H_{Te} &= 0 \text{ for } -HB_{T} < E_{Te} < +HB_{T} \end{aligned} \qquad [4]$$

Where Hψ is the output of the hysteresis comparator and HTe is the output of the torque hysteresis comparator, Eψ is the error in flux and $E_{Te}$ is error in torque, + HBψ,- HBψ are the positive and negative error bands of the flux hysteresis comparator and $+HB_{Te}$,$-HB_{Te}$ are the positive and negative error bands of the torque hysteresis comparator.

## 2.2. Flux, Torque estimation and Sector selection

The line currents of the Stator are sensed for estimating Torque and Flux. The Three Phase parameters are converted to Two Phase parameters with respect to stationary reference frame by using Clarke's Transformation for the convenience of computation.

- Clarke's Transformation

$$i_{qs} = \left(2/3i_a - 1/3i_b - 1/3i_c\right)(2)$$

$$i_{ds} = \left(-1/\sqrt{}3i_b + 1/\sqrt{}3i_c\right)(3)$$

$$= -1/\sqrt{}3\left(i_a + 2i_b\right)[1]$$

Here, ia, ib, ic are Stator line currents whereas, equations 2 and 3 shows the direct and quadrature axis currents where iqs, ids are represented as direct and quadrature axis currents.

$$v\ qs = (2/3v_a - 1/3v_b - 1/3v_c) = 1/3(v_{ab} + v_{ac}) \qquad (4)$$

$$v_{ds} = (-1/\sqrt{}3v_b + 1/\sqrt{}3v_c) = 1/\sqrt{}3\ v_{bc} \qquad (5)$$

The direct and quadrature components voltage are calculated using equations 4,5 where va, vb and vc are Stator phase voltages whereas, vqs is the quadrature axis phase voltage and vds is the direct axis phase voltages.

- Flux estimation

The Flux along direct and quadrature axis are estimated by

$$\psi_{ds} = \int \left(V_{ds} - Ri_{ds}\right) dt \qquad (6)$$

$$\psi_{qs} = \int \left(V_{qs} - Ri_{qs}\right) dt \qquad (7)$$

$$\psi_s = \sqrt{\psi_{ds}^2 + \psi_{qs}^2} \qquad (8)$$

$\psi_s$ represents the resultant stator flux linkage per phase.

- Torque estimation

From the above obtained Direct and quadrature axis flux and currents, The Electromagnetic torque is estimated by

$$T_e = (3/2).(p/2).\ (\Psi_{ds} - i_{qs} - \Psi_{qs}\, i_{ds}) \qquad (9)$$

Here, P/2 represents number of pole pairs in Induction motor.

- Sector selection

The angle between the resultant Flux linkage and reference axis is given by

$$a = Tan^{-1}\left(\frac{\psi_{qs}}{\psi_{ds}}\right) \tag{10}$$

The $\alpha$ value estimated is used for selecting the sector in which resultant flux linkage lies.

### 2.3. Switching table

Based on various combinations of the outputs of these hysteresis comparators a switching table is formed. The reference Torque and reference Flux can be achieved by selecting the suitable Switching states from the following table1.

Here, the division of the six sectors is shown as below

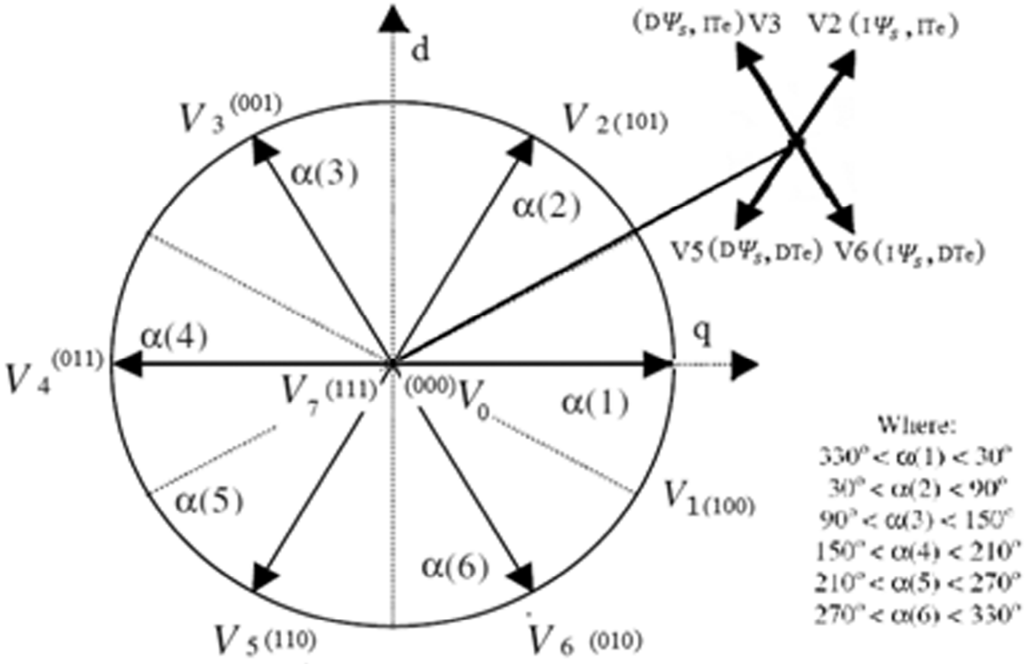


**Figure 2: Division of six sectors.**

- Effect on Flux

The resultant stator flux from a time period 0 to T is given by

$$\psi_s = \psi_0 + v_{s.}T - \int_0^T \left(i_s.R\right)dt \tag{11}$$

Here, the stator resistance voltage drop is negligble due to its small value.

Where, $\psi_0$ is the starting value of flux at time = 0.

The rate of change of Flux with respect to time is

$$\frac{d\psi_s}{dt} = \tag{12}$$

$$\Delta\psi_s = v_s.\Delta T \tag{13}$$

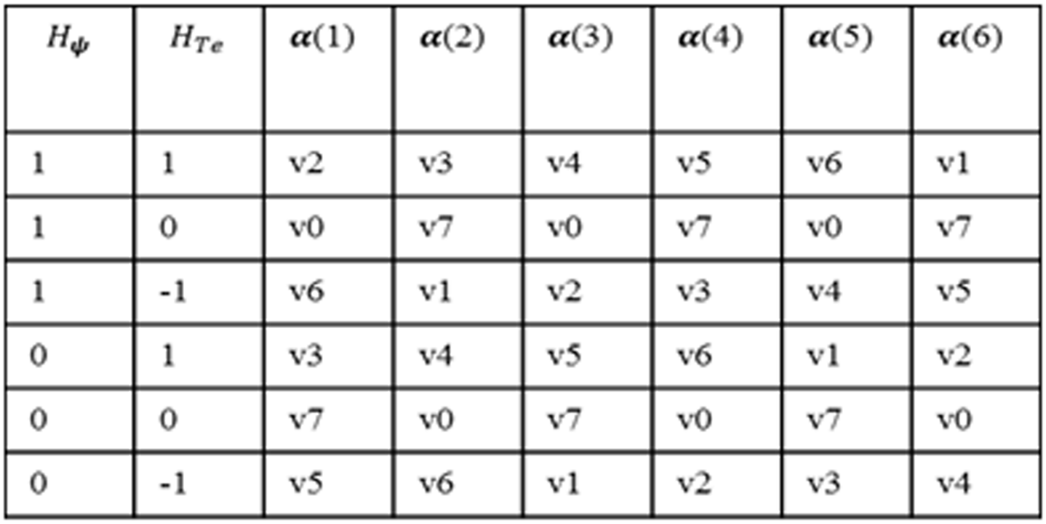
Therefore, the Flux is proportional to the magnitude of Vs.

- Effect on Torque

The electromagnetic Torque of an Induction motor depends on stator flux, rotor flux and relative position $\alpha$, which is given by

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\frac{L_m}{L_r\sigma}\right)|\psi_s||\psi_r|\sin\alpha \tag{14}$$

**Table 1**
**optimum voltage vector switching table.**



| $H_\psi$ | $H_{Te}$ | $\alpha(1)$ | $\alpha(2)$ | $\alpha(3)$ | $\alpha(4)$ | $\alpha(5)$ | $\alpha(6)$ |
|---|---|---|---|---|---|---|---|
| 1 | 1 | v2 | v3 | v4 | v5 | v6 | v1 |
| 1 | 0 | v0 | v7 | v0 | v7 | v0 | v7 |
| 1 | -1 | v6 | v1 | v2 | v3 | v4 | v5 |
| 0 | 1 | v3 | v4 | v5 | v6 | v1 | v2 |
| 0 | 0 | v7 | v0 | v7 | v0 | v7 | v0 |
| 0 | -1 | v5 | v6 | v1 | v2 | v3 | v4 |

## 3. FUZZY LOGIC CONTROL

Fuzzy is the control logic made in accordance with human's natural way of interpretation. The rules set of fuzzy are made based on various predictive ability of the humans. In case of PI controller it is very difficult to predict the exact value of kp and ki. Thus unexpected changes in the load conditions would produce overshoot, high ripple in torque, oscillation of the IMD, etc...[4]. This problem can be rendered by forming a fuzzy rule table as fuzzy does not require any details of kp and ki values and its response time is better than the PI controller. Mamdani type of fuzzy logic control is used in this model and the method used for De-fuzzification process is 'Centroid'. Fuzzification process involves these following stages as shown below

1) Two fuzzy input sets and one fuzzy output set for which each set will consists of seven subsets.
2) Fuzzification process using continuous class containing all entities referred to an argument.
3) Mamdani's minimum operator is used for implication.
4) The method used for Defuzzification process is centroid.

Fuzzification process is used to modify the numerical variable into linguistic variable also known as fuzzy number. The second stage De-fuzzification process is used for providing a computable fuzzy logic result for the provided fuzzy sets and membership degrees corresponding to it.

Data Base: The database stores the definition of the membership Function required by fuzzifier and defuzzifier [2].

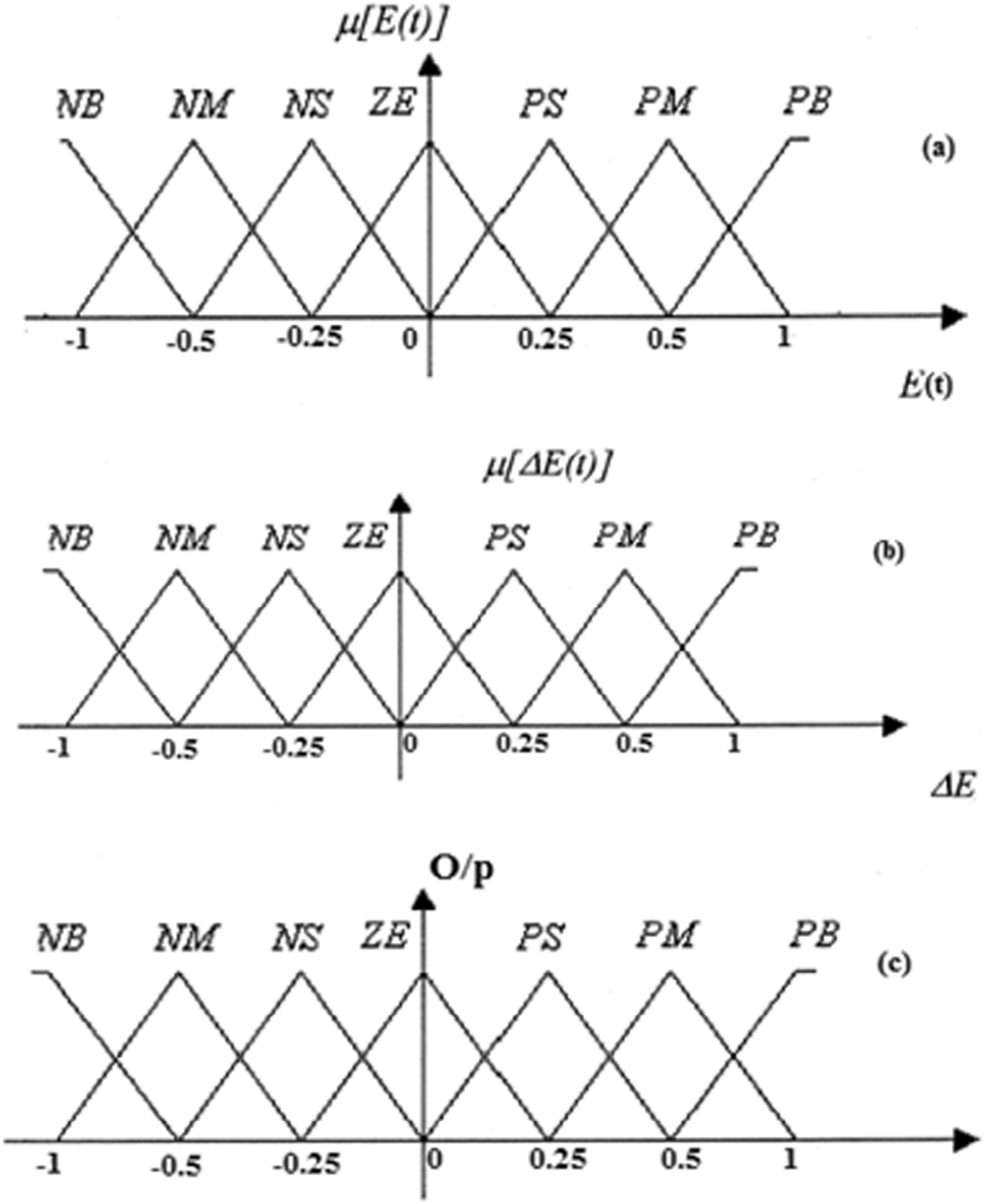


**Figure 3: The fuzzy membership functions of input variables (a) speed error, (b) rate of speed error, and (c) output variable.**

The following seven fuzzy sets are used for converting numerical values to linguistic values and their ranges are represented in fig.3.NB-Negative big, NM-Negative medium, NS-Negative small, ZE-Zero error, PS-Positive small, PM-Positive medium, PB-Positive big.

### 3.1. Fuzzy Variables

The speed error and the rate of speed error are considered as the input variables and are indentified using the state of membership functions in the provided fuzzy set. Triangular functions are used for defining this particular fuzzy sets.

### 3.2. Rules for Fuzzy control

This paper consists of two input variables each comprise of seven linguistic values, hence, overall 7*7 = 49 rules are obtained as shown in the table 2.

**Table 2**
**Control rules table**

| E<br>ΔE | NB | NM | NS | ZE | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | NB | NB | NB | NB | NM | NS | ZE |
| NM | NB | NB | NB | NM | NS | ZE | PS |
| NS | NB | NB | NM | NS | ZE | PS | PM |
| ZE | NB | NM | NS | ZE | PS | PM | PB |
| PS | NM | NS | ZE | PS | PM | PB | PB |
| PM | NS | ZE | PS | PM | PB | PB | PB |
| PB | ZE | PS | PM | PB | PB | PB | PB |

## 4. SIMULATION AND RESULTS

Both the models are simulated using MATLAB/SIMULINK and the results are shown in the following figures.

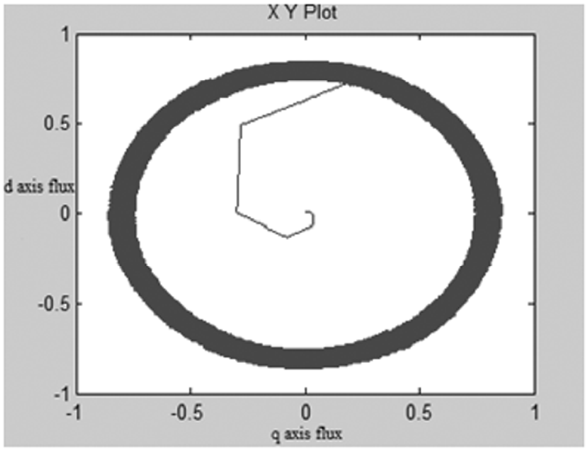


**Figure 4: Plot between direct axis flux and quadrature axis flux for classical DTC.**

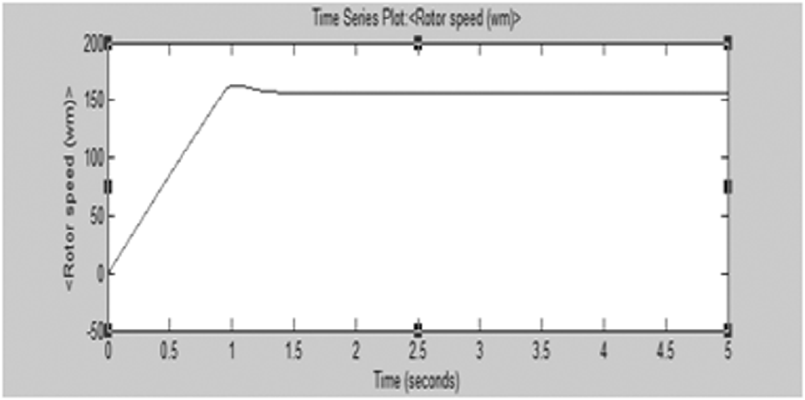


**Figure 5: Speed waveform.**

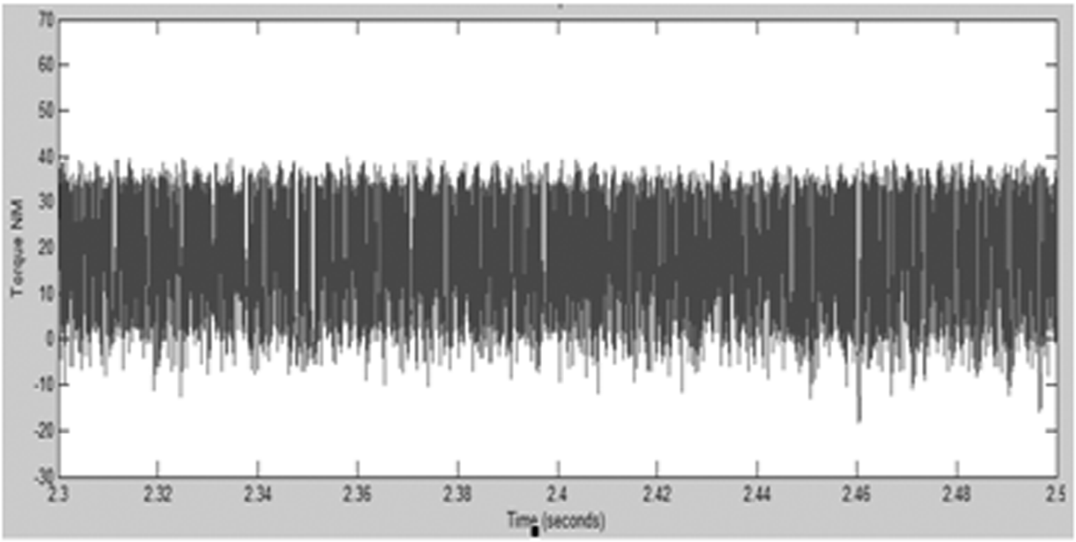


Figure 6: Torque waveform for classical DTC.

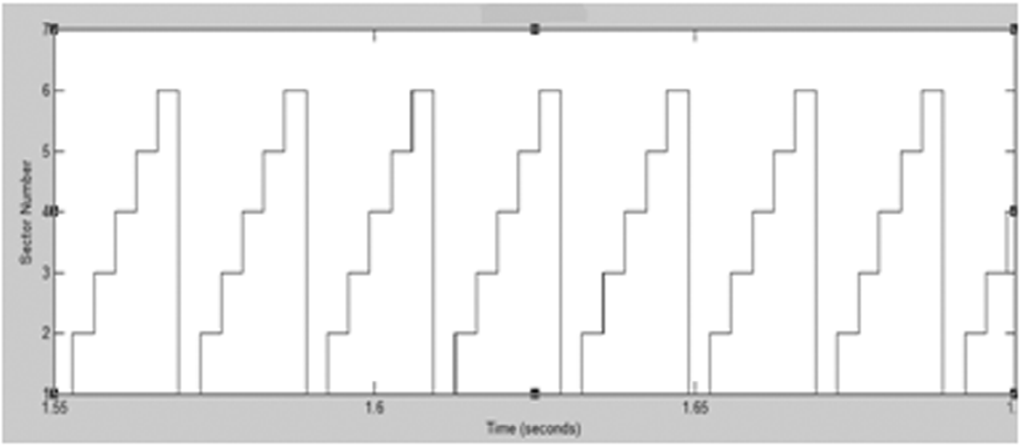


Figure 7: Waveform of Sectors.

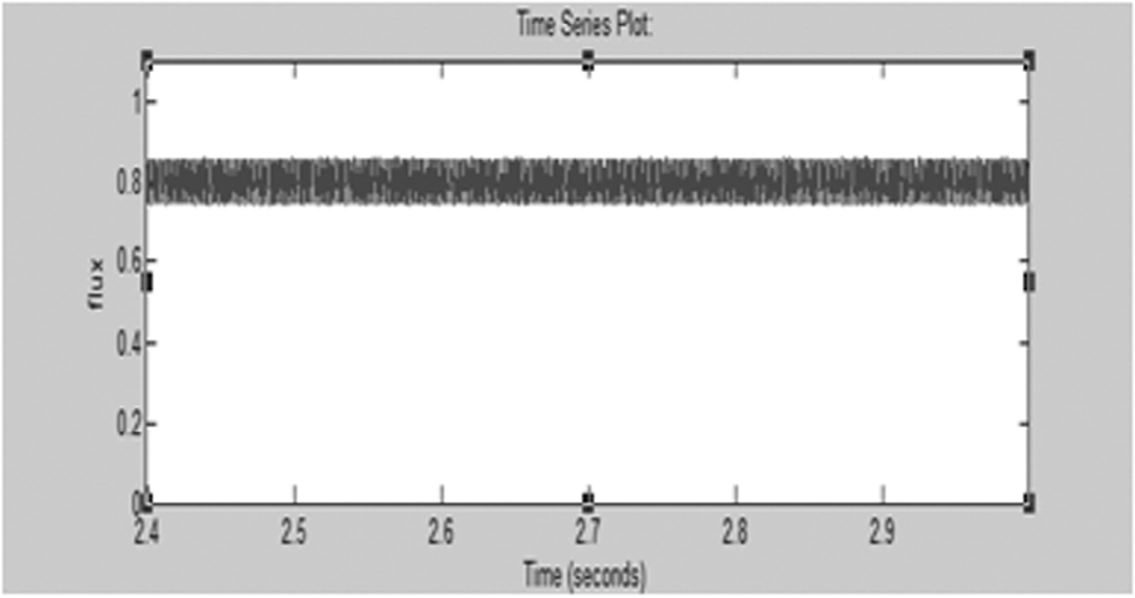


Figure 8: Flux waveform for classical DTC.

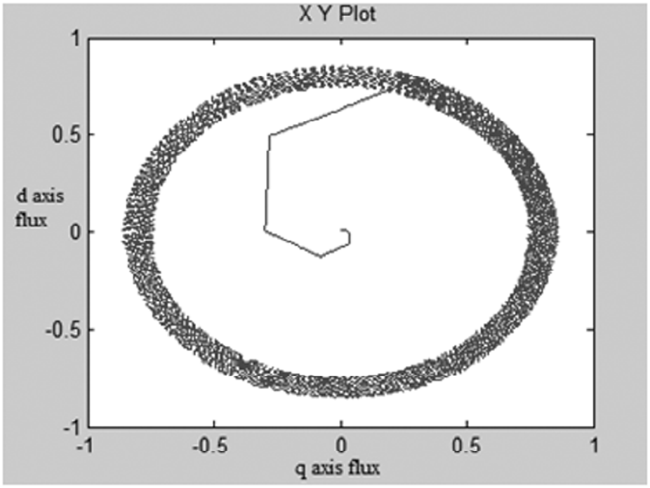


**Figure 9: Plot between direct axis flux and quadrature axis flux for FLC-DTC.**

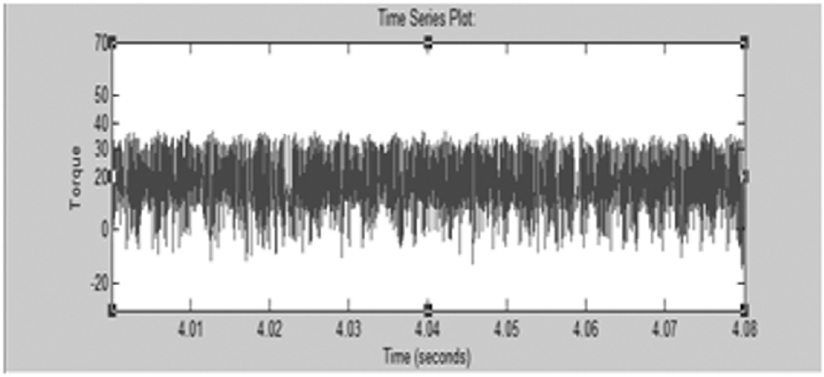


**Figure 10: Torque waveform for FLC- DTC.**

## 5. CONCLUSION

Direct torque control is an excellent technique to control the torque and flux independently. There are two separate hysteresis comparators for both flux and torque. The results of both the classical model and modified model are given and it is identified that the ripple in the torque is lesser in case of modified model and the transition is also smooth compared to classical model. So the adaptability of fuzzy for application purposes serves the individual in better way. The simulation results had shown a reduction in ripple of the torque compared to the classical one. Further more advanced control schemes like artificial neural network schemes, genetic algorithm schemes as informed in [9] can be implemented onto it for further improvement in quality of the IMD as research is going in those fields in a very great manner now a days.

## APPENDIX-I

| Parameter | Rating |
|---|---|
| Rated Power | 3.71KW |
| Voltage | 415V |
| Frequency | 50Hz |
| Rs | 0.087ohm |
| Rr | 0.237ohm |
| Poles | 4 |
| J | 0.086Kg/m^2 |
| Lm | 32.1mH |
| $L_{ls}$ | 1.24mH |
| $L_{lr}$ | 1.24 mH |

The induction motor parameters used are as shown below.

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