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DIRECT TORQUE AND FLUX CONTROL FOR SPEED REGULATOR OF AN INDUCTION MOTOR DRIVE USING COMBINED PI AND FUZZY LOGIC CONTROLLER

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ABSTRACT

This paper presents a simulation based solution for difficulty in speed regulation of IMD under Variable-Frequency condition. The speed control of the Variable-Frequency Drive is of two types; Scalar and Vector. Scalar Control is based on the relationships valid in the steady state conditions, only magnitude and frequency of voltage, current and flux linkage are controlled. Vector Control is based on relationships valid for dynamic states, not only magnitude but also instantaneous positions of voltage, currents and flux. Direct Torque Control is one of the Vector Control methods to control the Variable Frequency Drives. The torque and flux are controlled simultaneously by applying suitable voltage vectors, and by limiting these quantities within their hysteresis bands, de-coupled control of torque and flux can be achieved. The DTC control method has been optimized by using conventional PI controller in the SR loop of Induction Motor Drive.

The need for simple advanced control alternatives arises in Control Process. The application of Fuzzy Logic to wide range of control applications has made possible the establishment of Intelligent Controlling in the Control Processing. The main drawback of the DTC of IMD using conventional PI controller based SR is high torque, stator flux ripples and speed of IMD is decreasing under transient and steady state operating conditions. This drawback was eliminated using the FLC based SR loop. The FLC based SR control scheme combines the benefits of DTC technique along with FLC technique.

The work of this paper is to study, evaluate and compare the technique of the conventional DTC and DTC-FLC applied to the induction machines through MATLAB-2009a.

Keywords- *Conventional PI controller, Direct Torque Control (DTC), Fuzzy Logic Control (FLC), Induction Motor Drives (IMD), Space Vector Modulation (SVM).*

I. INTRODUCTION

The electric drives are used for motion control, now a day's around 70% of electric power consumed by electric drives only. This electric drives are mainly AC and DC drives. During last four decades AC drives are become more and more popular, especially induction motor Drives (lMD), because of high efficiency, high performance, and rugged structure ease of maintenance so widely used in industrial application, such as paper miles, robotics, steel miles, servos, transportation system, elevators, machines tools etc.

The IMD control methods can be divided into two methods such as, scalar and vector control. The general classification of the variable frequency controls is presented in Fig.l. After invention of power electronics components and scalar control method like Variable Frequency Drive (VFD)[10] or Slip Frequency Control, Induction Motors were widely used again but they didn't have de-coupling facility of torque and flux. So for the de-coupling of torque and flux, vector control introduced for better performance of Induction Motor application.

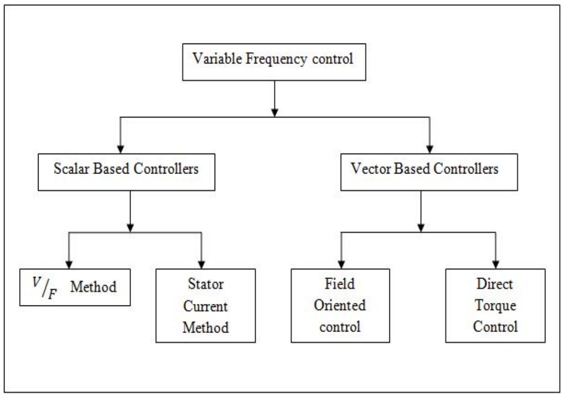

Fig.1 General Classification of Induction Motor Control Methods

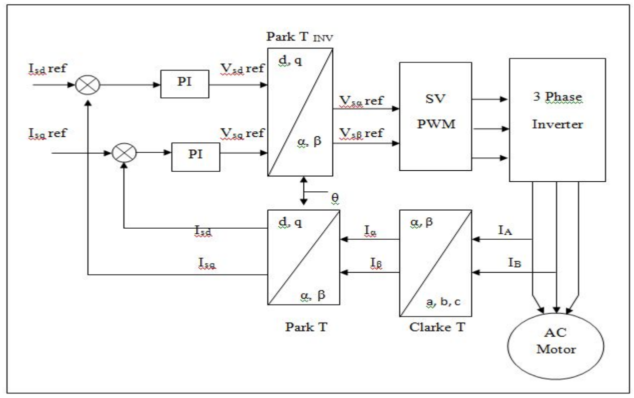

Fig. 2 Block Diagram of FOC

The scalar control is operating in steady state and controls the angular speed of current, voltage, and flux linkage in the space vectors. Thus, the scalar control does not operating in the space vector position during transient state. The vector control, which is based on relations valid for dynamic states, not only angular speed and magnitude but also instantaneous position of current, voltage, and flux linkage space vector are controlled. In the vector control, the most popular method for induction motor drives, known as Field Oriented Control (FOC) presented by F.Blaschke (Direct FOC) and Hasse (Indirect FOC) in early 1970's, gives high performance, and high efficiency for industrial applications [1].

In the FOC, the motor equations are transformed into a coordinate system that rotates in synchronism with the rotor flux vector control [2]. This drawback was eliminated using the new strategies for torque and flux ripple control of IMD using DTC was proposed by Isao Takahashi and Toshihiko Noguchi, in the mid 1980's [3]. The main feature of DTC is simple structure and good dynamic behavior and high performance and efficiency [4]. The new control strategies proposed to replace motor linearization and decoupling via coordinate transformation, by torque and flux hysteresis controllers [5]-[7].

This method referred as conventional DTC [8]. In the conventional DTC using PI based SR, there are more disadvantages, such as, variable switching frequency, high torque and flux ripple, problem during starting and low speed operating conditions, and flux and current distortion caused by stator flux vector changing with the sector position, in those most important is the speed of IMD is changing under transient state to steady state operating condition [9]. this drawback was eliminated using fuzzy logic control speed regulator instead of conventional PI speed regulator [10].

Vector control is the most popular control technique of AC induction motors. In special reference frames, the expression for the electromagnetic torque of the smooth-air-gap machine is similar to the expression for the torque of the separately excited DC machine. In the case of induction machines, the control is usually performed in the reference frame (d-q) attached to the rotor flux space vector. That's why the implementation of vector control requires information on the modulus and the space angle (position) of the rotor flux space vector. The stator currents of the induction machine are separated into flux- and torque-producing components by utilizing transformation to the d-q coordinate system. The block diagram of Vector Control is shown in Fig 2

II. DIRECT TORQUE AND FLUX CONTROL

A) Direct Torque Control

In 1980s an advanced scalar control technique named as direct torque control (DTC) For high power applications, Depenbrock proposed another control technique called as direct self control (DSC). DTC or DSC, by their names indicates the control of torque and flux directly. In DTC method, torque and flux hysteresis controllers are employed. The reference and actual values of torque and flux are compared and the signals are generated by the corresponding hysteresis controllers. A look up table arrangement generates the switching signals to the inverter.

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The inverter generates the variable voltages to the induction motor and hence can be controlled. In comparison with the vector control or the field oriented control method, DTC method is promising and can be effectively implemented. In this thesis DTC technique is employed to control the induction motor.

The electromagnetic torque in the three phase induction machines can be expressed as follows

$$T_e = \frac{3}{2}P(\varphi_s \times i_s) \quad 1$$

Where φ_s is the stator flux, i_s is the stator current (both fixed to the stationary reference frame fixed to the stator) and P the number of pairs of poles.

The basic relation between torque and machine fluxes is

$$T_e = \frac{3}{2}P\left(\varphi_{ds}^s i_{qs}^s - \varphi_{qs}^s i_{ds}^s\right) \quad 2$$

$$T_e = -\frac{3}{2}P\frac{K_r}{\sigma L_s}|\varphi_s| \times |\varphi_r| \sin\theta \quad 3$$

where θ, known as load angle between stator and rotor fluxes.

k_r = - Lm/Ls and σ = 1-Lm^2 / ($L_s L_r$). It is possible to achieve machine speed and torque control directly by actuating over the load angle.

B) DTC Controller

The way to impose the required 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

$$\frac{d\varphi_s}{dt} = V_s$$

or

$$\Delta\varphi_s = V_s . \Delta t \quad 4$$

Decoupled control of the stator flux modulus and 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. So imposing of proper voltage vector is important in direct torque control of Induction Motor. This we will obtained by using voltage source inverter.

C) DTC SCHEMATIC

In the following Fig 3, a possible schematic of the Direct Torque Control is shown. As it can be seen, there are two different loops corresponding to the magnitudes of the stator flux and torque. The reference values for the flux stator modulus and the torque are compared with the actual values, and the resulting error values are fed into the two-level and three-level hysteresis blocks respectively.

The outputs of the stator flux error and the torque error hysteresis blocks, together with the position of the stator flux are used as inputs of the look up table. The position of the stator flux is divided into six different sectors. In accordance with the Fig. 3, the stator flux modulus and torque error tend to be restricted within its respective hysteresis bands. It can be proved that the flux hysteresis band can affects to the stator current distortion in term of low order harmonics and the torque hysteresis ban affect the switching frequency.

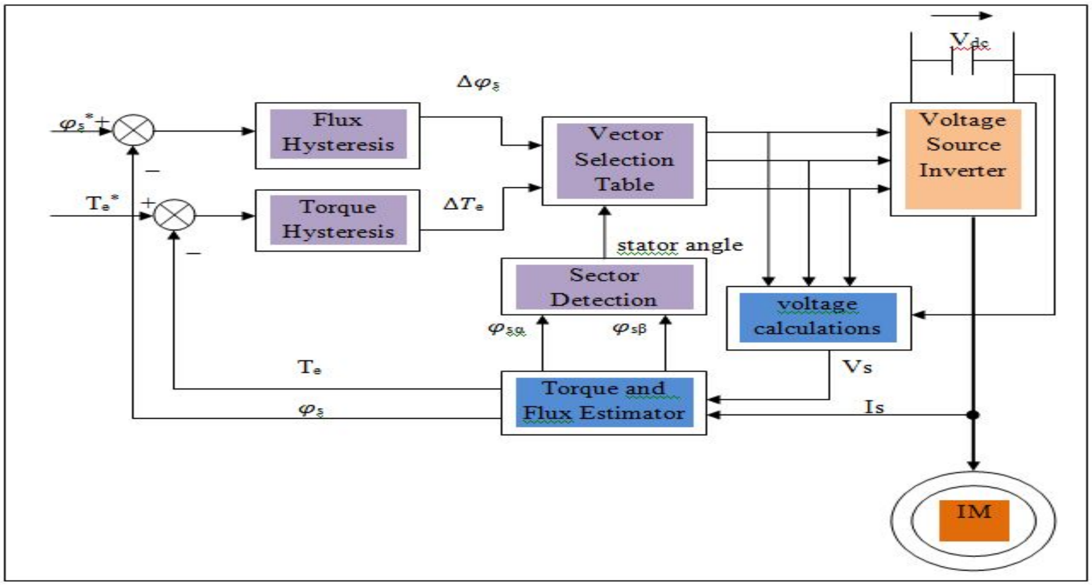

Fig. 3 Basic DTC Schematic Control

D) Torque Estimator

The equation 8 shows that the electromagnetic torque depends on the stator currents and the linkage fluxes. The stator currents are measurable quantities. There is electronic equipment that measures the current with great accuracy. On the other hand, the linkage flux is a quantity that is very difficult to be measured. This observation leads to the conclusion that the more accurate the estimation of the flux the more efficient the torque calculation.

The design of an appropriate sensor, which could measure the flux and could be placed between the stator and the rotor, would solve the problem. However, this idea, besides the constructional problems, could affect the magnetic fluxes in the motor and reduce its efficiency. On the other hand, torque estimation without any sensor, based on the mathematical model of the motor, could easily be used without any influence on the flux.

$$T_e = \frac{3}{2} P \left(\varphi_{ds}^s i_{qs}^s - \varphi_{qs}^s i_{ds}^s\right) \qquad 5$$

where

$$\varphi_{ds}^s = \int (V_{ds} - R_s i_{ds}) dt \qquad 6$$

$$\varphi_{qs}^s = \int (V_{qs} - R_s i_{qs}) dt \qquad 7$$

and thus the final torque equation is given by

$$T_e = \frac{3}{2} P \left(i_{qs}^s \int (V_{ds} - R_s i_{ds}) dt - i_{ds}^s \int (V_{qs} - R_s i_{qs}) dt\right) \qquad 8$$

The final torque equation depends on the stator voltage, stator currents and the resistance of stator phases quantities that can be measured accurately. Actually, the variation of the stator resistance with time/temperature is significant. The equations are very sensitive to the resistance, especially at low speed.

E) Flux Estimator

In the direct vector control method, as discussed above, it is necessary to estimate the rotor flux components Ψ_{dr}^s and Ψ_{qr}^s so that the unit vector and rotor flux can be calculated by equations 9 and 10. The commonly used method of flux estimation is discussed.

$$\Psi_{dr}^s = \hat{\Psi}_r \cos\theta_e \qquad 9$$

$$\Psi_{qr}^s = \hat{\Psi}_r \sin\theta_e \qquad 10$$

$$\cos\theta_e = \frac{\Psi_{dr}^s}{\hat{\Psi}_r} \quad ; \quad \sin\theta_e = \frac{\Psi_{qr}^s}{\hat{\Psi}_r} \qquad 11$$

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$$\Psi_r = \sqrt{{\Psi_{dr}^s}^2 + {\Psi_{qr}^s}^2} \qquad 12$$

Where vector Ψ_r is magnitude of $\overline{\Psi}_r$ the unit vector signals ($\cos\theta_e$ and $\sin\theta_e$) when used for vector rotation, give a ride of current ids on the d-axis (direction of Ψ_r) and current iqs on the q-axis as shown. At this condition $\Psi_{qr}=0$ and $\Psi_{dr}=\Psi r$, as indicated and the corresponding torque expression is given by equation (8) like a dc machine. When the iqs polarity is reversed by the speed loop, the i_{qs} position also reverses, giving negative torque. The generation of a unit vector signal from feedback flux vectors gives the name "direct vector control".

In voltage based method, the machine terminal voltages and currents are sensed and the fluxes are computed from the stationary frame (d_s-q_s).

$$i_{qs}^s = \frac{2}{3}i_a - \frac{1}{3}i_b - \frac{1}{3}i_c = i_a \qquad 13$$

$$i_{ds}^s = -\frac{1}{\sqrt{3}}i_b - \frac{1}{\sqrt{3}}i_c \qquad 14$$

$$= -\frac{1}{\sqrt{3}}(i_a + 2i_b) \qquad 15$$

Since $i_c=-(i_a+i_b)$ for isolated neutral load

$$v_{qs}^s = \frac{2}{3}v_a - \frac{1}{3}v_b - \frac{1}{3}v_c \qquad 16$$

$$= \frac{1}{3}(v_{ab} + v_{ac}) \qquad 17$$

$$v_{ds}^s = -\frac{1}{\sqrt{3}}v_b + \frac{1}{\sqrt{3}}v_c \qquad 18$$

$$= -\frac{1}{\sqrt{3}}v_{bc} \qquad 19$$

$$\Psi_{ds}^s = \int(v_{ds}^s - R_s i_{ds}^s)dt \qquad 20$$

$$\Psi_{qs}^s = \int(v_{qs}^s - R_s i_{qs}^s)dt \qquad 21$$

$$\Psi_r = \sqrt{{\Psi_{ds}^s}^2 + {\Psi_{qs}^s}^2} \qquad 22$$

$$\Psi_{dm}^s = \Psi_{ds}^s - L_{ls}i_{ds}^s = L_m(i_{ds}^s + i_{dr}^s) \qquad 23$$

$$\Psi_{qm}^s = \Psi_{qs}^s - L_{ls}i_{qs}^s = L_m(i_{qs}^s + i_{qr}^s) \qquad 24$$

$$\Psi_{dr}^s = L_m i_{ds}^s + L_r i_{dr}^s \qquad 25$$

$$\Psi_{qr}^s = L_m i_{qs}^s + L_r i_{qr}^s \qquad 26$$

Eliminating i_{dr}^s and i_{qr}^s from above two equations with the help of 25 and 26 we get the following

$$\Psi_{dr}^s = \frac{L_r}{L_m}\Psi_{dm}^s - L_{lr}i_{ds}^s \qquad 27$$

$$\Psi_{qr}^s = \frac{L_r}{L_m}\Psi_{qm}^s - L_{lr}i_{qs}^s \qquad 28$$

The Torque and Flux are calculated from the Torque and Flux estimator. The estimated Flux is calculating by the integrating of applied stator voltage. And the estimated Torque is obtained from the vector product of Flux and Currents. The estimated values are compared with the reference values and the passed through hysteresis band [9] controller in order to check the error is within the tolerance. Based on the Torque, Flux and the stator angle, the output of VSI is varied which is applied to the Induction Motor and thus the Speed and Torque is controlled.

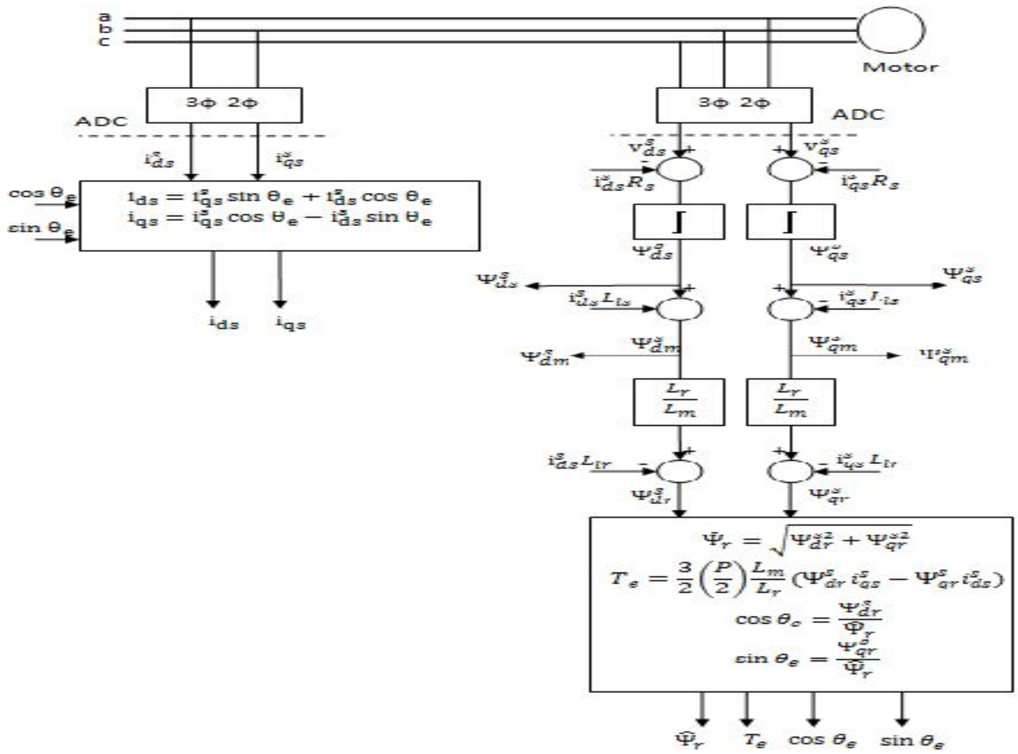

Fig. 4 Block Diagram of Feedback Signal Estimation

III. CONTROL SYSTEM

The computer is able to execute the rules and compute a control signal depending on the measured inputs error and change in error. Therefore the rules reflect the strategy that the control signal should be a combination of the reference error and the change in error. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made. The process of fuzzy inference involves membership functions, fuzzy logic operators, and if-then rules. The type of fuzzy inference systems that can be implemented in the fuzzy logic toolbox which is Mamdani-type. The basic structure of a F.L.C as illustrated in Fig 5 below consists of the following components.

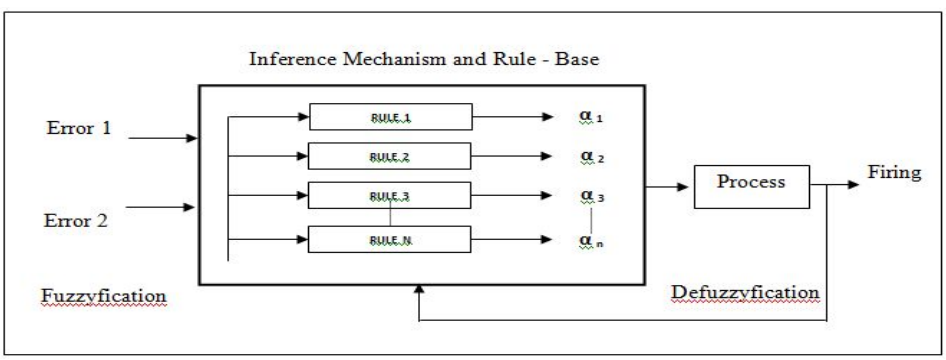

Fig 5 Basic FLC

A) Fuzzy Control Rules

In the fuzzy membership function there are two input variables and each input variable have five linguistic values, so 5x5=25 fuzzy control rules are in the fuzzy reasoning is shown in TABLE. I, and flowchart of FLC is shown in Fig.6.

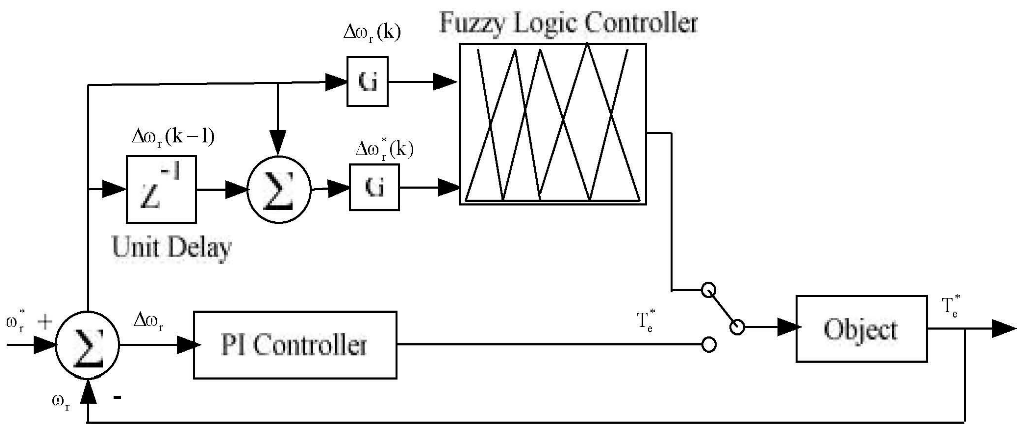

Fig 6. The structure of Fuzzy logic control based speed regulator.

TABLE 1 Fuzzy CONTROL RULES

$\Delta\omega_r^*(k)$ / $\Delta\omega_r(k)$	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NL	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PL	PL
PL	ZE	PS	PL	PL	PL

B) Fuzzy PI-Controller Based DTC

Fig 7 shows the structure of the fuzzy PI controller for Direct Torque Control DTC [2]. The main feature of this schemes is the fuzzy self adaptation of PI controller block.

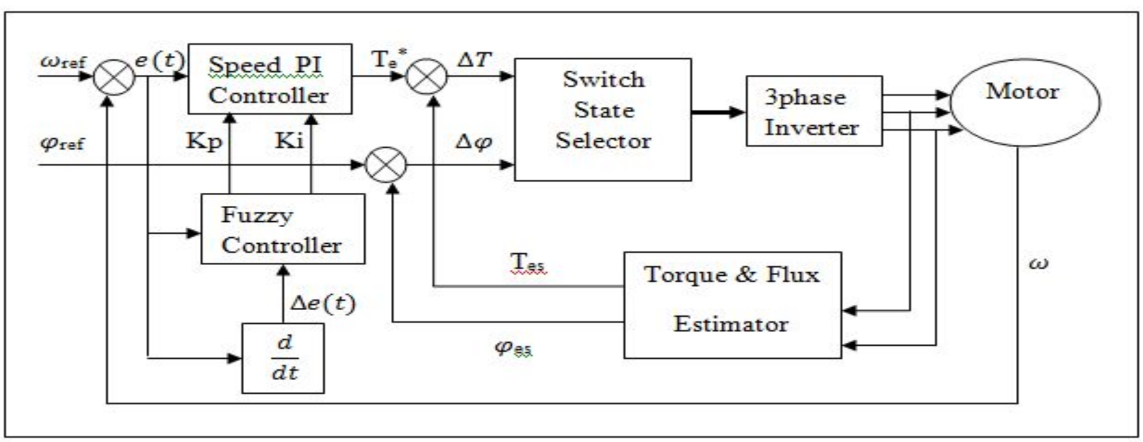

Fig 7 Fuzzy PI-Controller Based DTC

In this method a scaled values of speed error and change of speed error are used by the fuzzy controller to updated the values of proportional gain Kp and integral gain Ki, [6] by using a set of rules to have excellent control performance even for parameter variations and non-linearity characteristics of the drive system
.

IV. SIMULATION RESULTS AND CONCLUSIONS

Fig. 8 shows the simulink diagram for simulation of Direct Torque Control of Induction Motor. Main subsystems are the voltage conversion (three phase to two transformation), torque & flux estimator and speed regulator. The simulink diagram is shown in Fig 8 is constructed according to the block diagram of DTC of Induction Motor (Fig 4). The subsystems are modeled with respect to the equations and respective theory. The estimated values of the flux and Torque is calculated from the dq parameters of voltage and currents. The reference torque is calculated from the speed error and compared with the estimated torque and the torque error is passed through torque hysteresis band in order to check the error is within the limit or not. In the flux hysteresis band, the estimated flux is compared with reference flux. Based on the flux, torque and theta, the voltage vector is selected and thus the inverter output is varied to control the Induction Motor.

In the DTC of IMD using conventional PI controller based SR are requires the precise mathematical model of the system and appropriate gain values of PI controller to achieve high performance drive. Therefore, unexpected change in load conditions would produce overshoot, oscillation of the IMD speed, long settling time, high torque ripple, and high stator flux ripples. To overcome this problem, a fuzzy control rule look-up table is designed from the performance of speed response of the DTC of IMD. According to the speed error and change in speed error, the proportional gain values are adjusted on-line.

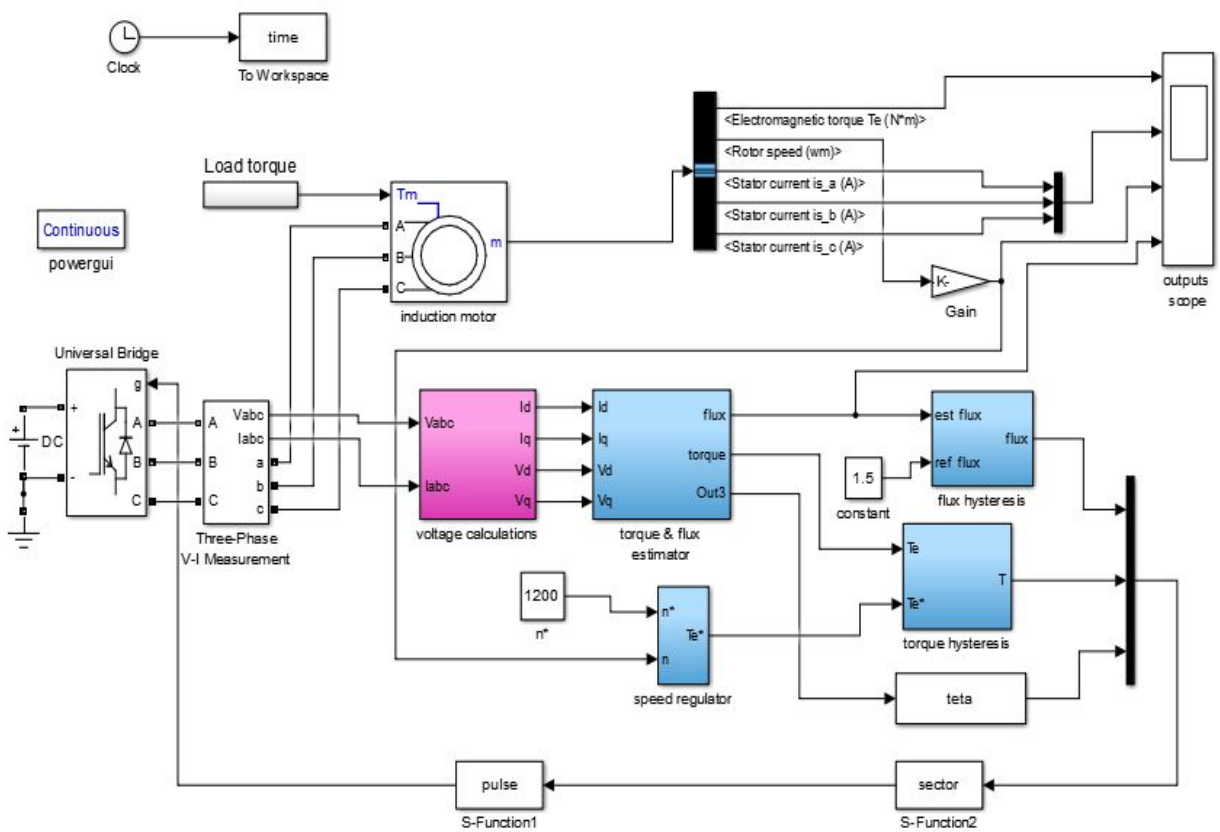

Fig 8 Simulink Model of DTC of Induction Motor

In the fuzzy based speed regulator, the output of the fuzzy logic is depends on the inputs applied to it. A set of rules is implemented in fuzzy logic and based on the speed error and change in speed error applied to fuzzy logic, thus the reference torque is obtained T_e^* .

Stator Currents

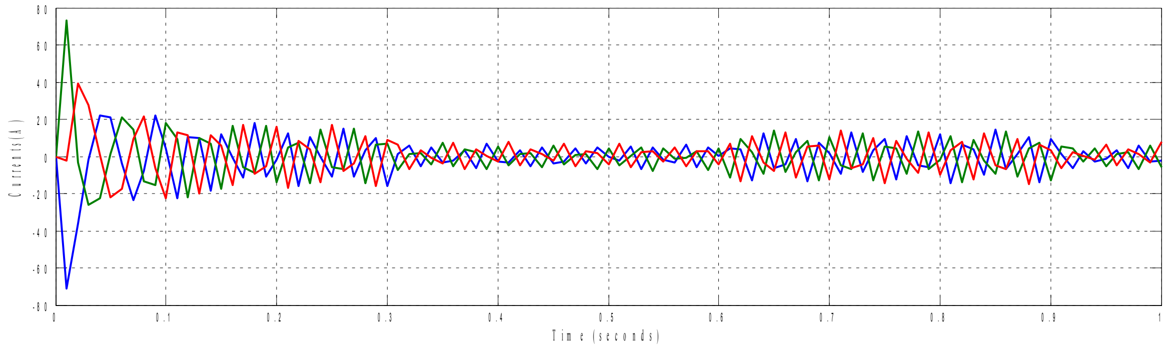

Fig. 9 Stator Currents of IM Using Conventional DTC

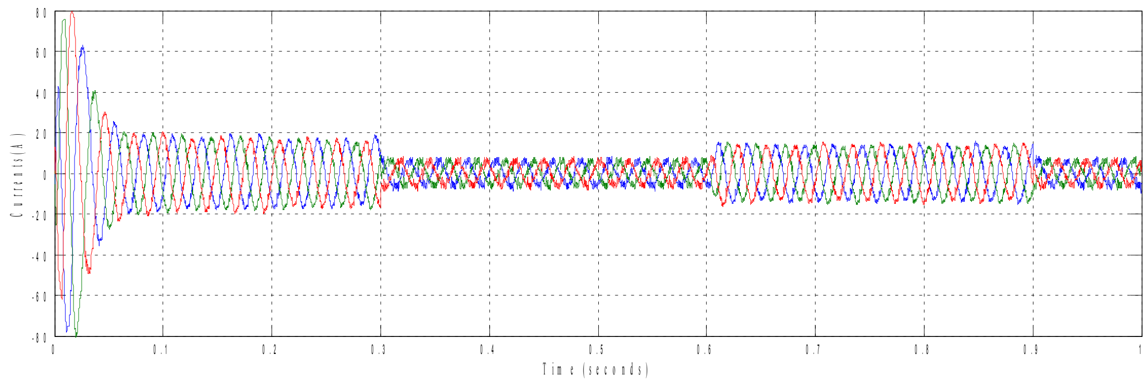

Fig.10 Stator Currents of IM Using DTC -FLC

The above Figs 9 and 10 shows the currents waveforms using both conventional and fuzzy logic control of IM. At the time of start, high starting ripples are observed in conventional DTC where as the ripples are low in fuzzy logic DTC. A load is applied (at t= 0.6) the current is increased in both the control schemes but during loading conditions also the little higher ripples are observed (Fig 9) in conventional DTC.

Torque

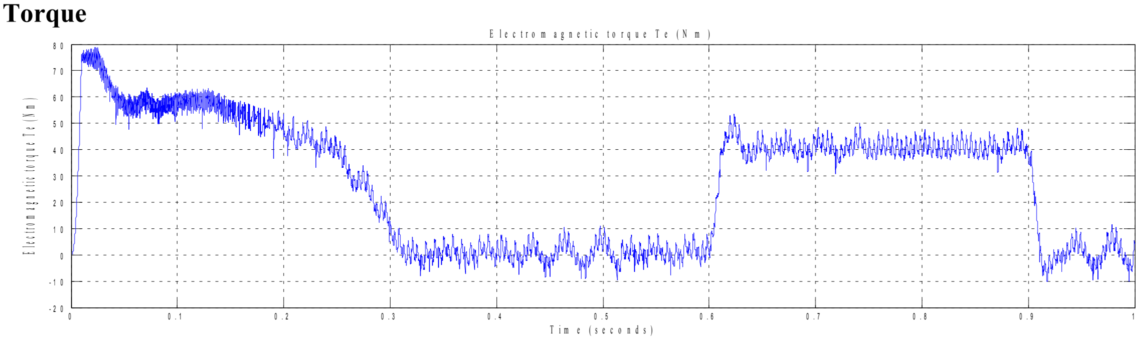

Fig 11 Torque of IM Using Conventional DTC

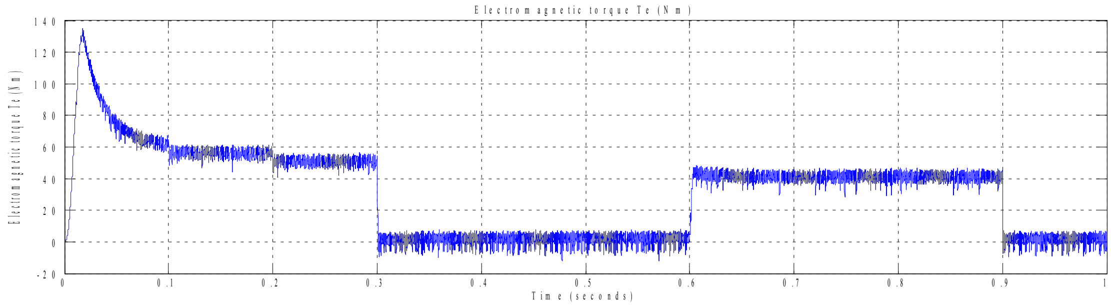

Fig 12 Torque of IM Using DTC -FLC

In Figs 11 and 12 shows the torque waveform of IM using conventional DTC and fuzzy control of IM respectively. In Fig, the starting ripple content is higher than the fuzzy control as shown in Fig 6.5. During loading (t= 0.6 and load is 40 N-m) the fuzzy control produces lower ripple content. By using FLC, high quality of torque is achieved.

Speed

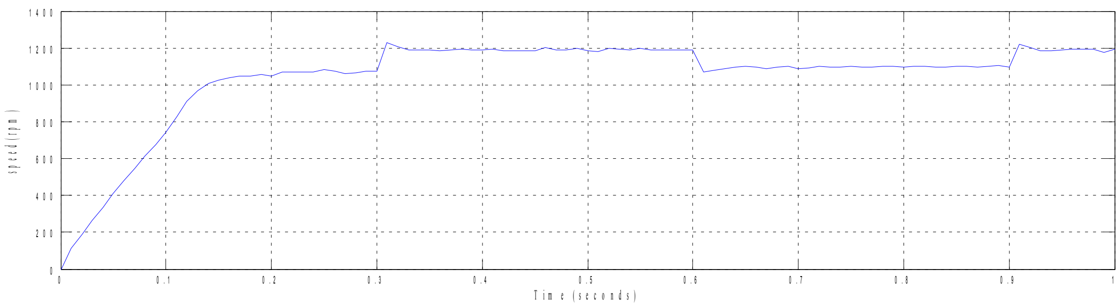

Fig 13 Speed of IM Using Conventional DTC

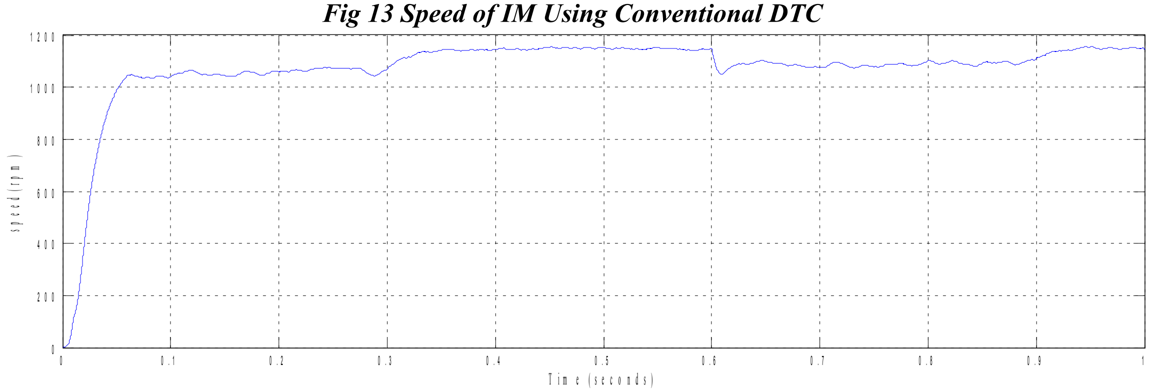

Fig 14 Speed of IM Using DTC -FLC

The IM attained its reference speed at t = 0.3, but the speed ripples in FLC is lower when compared to conventional control. At loading (t = 0.6) the speed is decreased (torque is increased) to drive the load in both the control schemes. After removal of load (t = 0.8), a little ripples are observed in conventional control of IM where as the constant speed is obtained in FLC of IM. At the of starting the higher ripples are obtained.

V. CONCLUSION

In this paper a simple approach for torque, flux, and speed regulating of direct torque controlled IMD using both conventional PI and FLC has been presented, among both of them FLC based SR is superior for the low torque, stator flux ripples, and maintained rated speed under transient and steady state operating conditions. Also the torque and flux can be directly controlled with the inverter voltage vector using space vector modulation technique. Two independent torque and flux hysteresis controllers are used in order to control the limits of the torque and stator flux ripples.

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From the simulations results it is showed that the Fuzzy Logic Control of DTC Induction Motor is good for the reduction of Torque and Currents when compared to the Conventional DTC with PI controller, and thus tabulated in table No. II shown below.

Table II Comparision between DTC-PI and DTC FLC

Parameter	DTC-PI	DTC -FLC
Control method	Conventional	Artificial Intelligence
Ripple content	High	Low when compared DTC-PI
Gian values (PI values)	Fixed	Adopted Online
Cureent ripples	High	Reduced
Speed	Low Ripples observed after steady state also.	No ripples after steady state

The flux and speed graphs in both the methods, the waveforms are close to each other. But the ripples in torque and currents using conventional DTC- PI is higher that of the DTC -FLC

VI. FUTURE SCOPE

In all aspects of Induction Motor control and new applications demanding future refinement, further research needs to be done. The control structure can be formulated and implemented with DSP Processor.

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