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Direct Torque Conrol of Induction Motor with PI and Fuzzy tuned PI based Speed Regulators

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***Abstract*— Induction Motors are beginning point to design an electrical drive system that is wide utilized in Industrial applications. The basic theory of operation of Induction Motor is presented and Direct torque Controlled Induction Motor Drive is simulated in MATLAB.**

In Conventional Direct Torque Control (DTC), the determination of flux linkage and electromagnetic torque errors are made inside particular flux and torque hysteresis bands, aiming to get fast torque response, low inverter switching frequency and low harmonic losses. DTC drives using hysteresis comparators experience variable switching frequency and high torque ripple. Space Vector Modulation (SVM) is the procedure to minimize torque ripple of induction motor in which, stator flux level is chosen as per the efficiency value. By using this technique, along with speed regulator, speed are often controlled also as torque ripples will be reduced.

In this thesis work, the simulation of DTC scheme with PI and Fuzzy tuned PI speed regulator (SR) has been carried out in MATLAB/SIMULINK and a comparison between them is formed.

Keywords*— *Direct Torque Control; Space Vector Modulation; Speed Regulators; Induction Motor

I. INTRODUCTION

Over the previous decades, DC machines were utilized broadly for variable speed applications because of the decoupled control of torque and flux that can be accomplished by armature and field current control individually. DC drives are worthwhile in numerous perspectives as in conveying high starting torque, simplicity of control and non linear performance. But due to major drawbacks of DC machine like presence of mechanical commutator and brush assembly, DC machine drives are using rarely for industrial applications.

The robustness, low cost, the better performance and simple maintenance create the asynchronous motors advantageous in several general or industrial applications. Squirrel cage induction motors (SCIM) are most generally used than remainder of electrical motors as they need all benefits of AC Motors and are cheaper in price compared to slip ring induction motors. Also, it requires less maintenance and has got a rugged construction. As slip rings are absent in SCIM, brushes maintenance duration and price associated with the wear and tear of brushes are reduced. Due to these advantages, the induction motors have been the execution element of most of the electrical drive system for all connected aspects: starting, braking, speed change and speed reversal etc.

The basic concept of direct torque control (DTC) of induction-motor is to regulate each stator flux-linkage and electromagnetic torque of the machine at the same time by employing a switching vector look-up table. As voltage, current and speed are the key issue in the direct torque control, these are the solely governable factors within the induction motor. The basic concept of direct torque control (DTC) of IM drives is to regulate each stator flux-linkage and electromagnetic torque of the machine at the same time by employing a switching vector look-up table. The DTC structure is simple compared to a vector control rule, because it will not need coordinate transformation and voltage modulation block, and thus, can be implemented comparatively simply

In addition, it has fast dynamic performance. While DTC is widely used as a result of these benefits, it has disadvantages like high ripples in torque and attainable problems throughout start or low speed operation and through changes in torque command. To overcome these shortcomings, various approaches for flux and torque ripple reduction. The basic scheme of DTC is preferred in high power range applications, where a lower inverter switching frequency will justify higher current distortion. DTC allows a sensible torque control in steady state and transient operating condition.

II. LITERATURE SURVEY

A. Induction Motor

Induction Motors have been widely employed in constant speed drives, for loads requiring severe starting conditions and for loads requiring low starting torque . These motors have significant benefits, attracting the interest of researchers and industry for use in several applications. They are common owing to their ruggedness, simplicity, low cost and less maintenance charges. The most common applications are centrifugal pumps, most machinery tools, reciprocating pumps, fans, punching presses, shears, hoists, cranes, elevators, wood working tools, compressors, crushers, etc. So, induction motors have wide area of applications [9].

Depending on variety of rotor construction, induction motors are of 2 types:-

1. Squirrel Cage induction motor.
2. Wound-rotor motor, also known as slip ring induction motor.

These two sorts of induction motor differ by the development of rotor, having certain benefits and disadvantages over one another.

The popularity of Induction motors comes from their attractive features:

- They have inherent self starting torque.
- They require no dc excitation.
- They can operate at lagging power factor.
- Speed control is possible.
- Lower maintenance cost.
- Simplicity.
- Compact structure.
- Constant speed.

However, induction motors will be used to provide solely mechanical loads and they can operate at lagging power factors that makes them restrictive for a few applications.

Induction motors are being used quite ever before in industry and individual machines of up to 10 MW in size are no longer a rarity.

III. DIRECT TOQUE CONTROL OF INDUCTION MOTOR

A.GENERAL DESCRIPTION

Nowadays “induction motor control techniques” are the area of interest of many researchers to notice out totally different solutions for induction motor control having the options of precise and fast torque response, and reduction of the complexity of field oriented control. The Direct torque control (DTC) technique has been recognized as the straightforward and viable solution to realize this necessities.DTC is one of the foremost excellent and efficient control ways of induction motor. This technique relies on decoupled management of torque and stator flux and nowadays it's one among the foremost actively researched control techniques where the aim is to manage effectively the torque and flux [2] , [8] ,[10].

In the DTC of induction motor, flux linkage, and electromagnetic torque are directly controlled by the choice of a switching vector from a look-up table. The DTC is one of the foremost excellent direct control methods of stator flux and torque ripples of IMD [5], [11]. Main features of direct torque control are:

1. Torque and flux can be modified very fast by changing the references.
2. High efficiency and low losses - switching losses are decreased as results of the transistors are switched solely once it's needed to stay torque and flux within their hysteresis bands.
3. No overshoot in step response.
4. Coordinate transforms are not needed; all calculations are done in stationary reference frame.
5. No separate modulator is needed; the switch control signals are defined by hysteresis controllers.
6. There are no PI current controllers. Thus no tuning of the management is needed
7. Even if switching frequency of the transistors is not constant, the average switching frequency will be kept at its reference *value* by controlling the width of the tolerance bands. This also reduces the current and torque ripple.
8. Synchronization to rotating machine is straight forward as a result of the fast control; simply make the torque reference zero and start the inverter. The flux will be identified by the first current pulse
9. The typical DTC includes two hysteresis controllers, for torque error correction and for flux linkage error correction [7], [14]. The hysteresis flux controller keeps the stator flux rotate in a circular fashion. The hysteresis torque controller keeps the motor torque within a predefined hysteresis band. The control algorithm determines the control signal whose amplitude depends on difference between desired value and actual value.

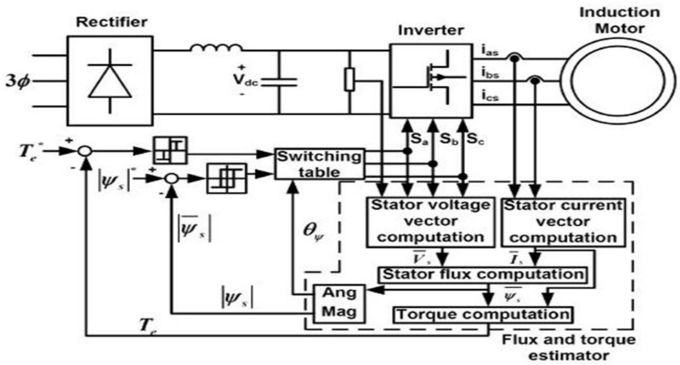

Figure 1. Block Diagram of Direct Torque Control

B.BASIC PRINCIPLE OF DTC

The block diagram of a DTC fed Induction Motor drive is shown in Figure 1. Here, the stator currents are transformed into d-q reference for the control of Induction Motor torque that involve determination of both torque and flux errors. These errors help switching look up table to pick proper voltage vector required to drive IM. Stator voltage vector estimates the flux by using equation:

$$\psi_s = \int (V_s - R_s i_s)\, dt$$

Stator flux linkage amplitude can be controlled by applying a required voltage vector. To select the voltage vectors for controlling the stator flux linkage the voltage plane is divided in to 6 regions [6], [13].

The Induction Motor Torque in rotor referance frame is given by:

$$T_e = \frac{3}{2} P \left[\psi_d i_q - \psi_q i_d\right]$$

Induction Motor torque can be estimated from the calculated currents and fluxes in the stationery reference frame.

The estimated torque and flux are compared to their command values. The difference between command values is compared in hysterisis comparator.Torque error is processed in a three layer hysterisis band and flux error is processed in a double layer hysterisis band.

The torque hysteresis loop controller has 3 levels of digital output, which have the following relations is shown in Table 1.

State	Torque Hysteresis
$(T_e - T_e^*) > \Delta T_e$	1
$-\Delta T_e < (T_e - T_e^*) < \Delta T_e$	0
$(T_e - T_e^*) < -\Delta T_e$	-1

Table 1. Switching logic for torque error

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Vol. 5 Issue 05, May-2016

When the torque hysteresis band is $\mathbf{T_e}$ =1 increasing torque, when $\mathbf{T_e}$= 0 means torque at zero and $\mathbf{T_e}$ = -1 decreasing the torque.

A stator flux error ($\Delta\psi_s$), thus determines which voltage vector has to be called, which is converted to the error state signal ψ using hysteresis flux controller with ($\Delta\psi_s$) hysteresis band. The flux hysteresis loop controller has 2-level of digital output ψ, according to the following relation shown in Table 2 below:

State	Flux Hysteresis
$(\psi_s^* - \psi_s) > \Delta\psi_s$	1
$(\psi_s^* - \psi_s) < -\Delta\psi_s$	0

Table 2. Switching logic for flux error

Voltage vector selection and Control of Voltage space vector in six sectors of flux plane is shown in Table 3 given below:

Hysteresis Controller		Sector Selection θ_e (k)					
ψ	T	Sector $\theta_e(1)$	Sector $\theta_e(2)$	Sector $\theta_e(3)$	Sector $\theta_e(4)$	Sector $\theta_e(4)$	Sector $\theta_e(4)$
1	1	U2 110	U3 010	U4 011	U5 001	U6 101	U1 100
	0	U7 111	U8 000	U7 111	U8 000	U7 111	U8 000
	-1	U6 101	U1 100	U2 110	U3 010	U4 011	U5 001
0	1	U3 010	U4 011	U5 001	U6 101	U1 100	U2 110
	0	U8 000	U7 111	U8 000	U7 111	U8 000	U7 111
	-1	U5 001	U6 101	U1 100	U2 110	U3 010	U4 011

Table 3. Voltage vector selection

C. PI CONTROLLER

It is one of the well known controllers used in a very wide range in the industrial applications. The PI controller output in time domain is defined by the following equation:

$$V_c(t) = k_p e(t) + k_i \int_0^t e(t)\,dt$$

The difference between the speed is calculated by speed controller producing an error, which is fed to the PI controller. These controllers are widely used for motion control systems [1] , [4].

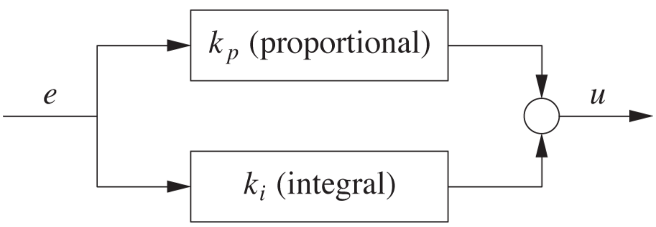

Figure 2. Block Diagram of PI Controllers

They consist of a proportional gain that produces associate output proportional to the input error and integration gain to attenuate the steady state error zero for a step change in the input.

D. FUZZY CONTROLLER

The Fuzzy Logic Controller (FLC) is the rule based, non-linear controller which takes the analog inputs and analyses it by converting it to logical variables and gives the output by defuzzification [3]. In this case we are considering the speed error (e) and change in speed error as inputs for the controller. But the performance of the fuzzy controller as compared to the PI controller is superior mainly under transient conditions [12].

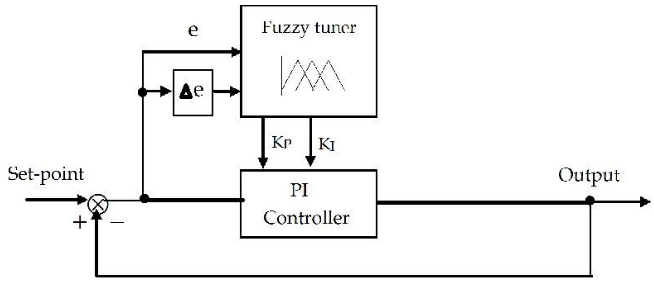

Figure 3. Block Diagram of Fuzzy tuned PI Controllers

The main drawback of this PI controller is the occurrence of overshoot at the time of starting and load removal also undershoots while application of load [1], [4]. For the removal of these drawbacks Fuzzy controller is used along with PI controller. The block diagram of Fuzzy tuned PI Controller is shown in Figure 3.The membership functions, fuzzy rules and their distribution determine the performance of the Fuzzy Controller.

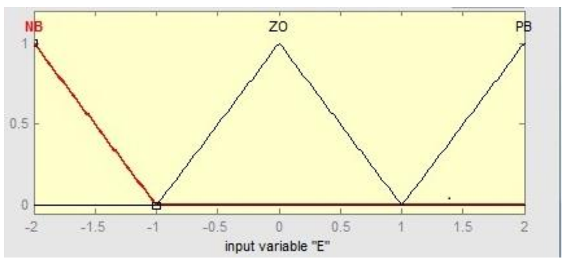

Figure 4. Membership Function and Input Variable

In the DTC scheme using Fuzzy Control in voltage source inverter-fed induction motor drive system, simultaneous control of the flux linkage and torque is required. Thus, the reference torque to DTC is fed from speed loop of the IM drive which is regulated by using FLC. Input linguistic variables are speed error (E), change in speed error (CE) and output linguistic variables are Kp and Ki.The Membership function for Input variable is shown in Figure 4.

International Journal of Engineering Research & Technology (IJERT)
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Vol. 5 Issue 05, May-2016

E / EC	NB	ZO	PB
NB	Z	B	Z
ZO	Z	Z	B
PB	Z	B	B

Table 4. Membership Function Rules

Knowledge base involves shaping the rules represented as IF-THEN statements governing the connection between input and output variables by using membership functions. In this stage, the variables Error (E) and Change in error (CE) are processed by an logical thinking that executes nine rules as shown in Table 4.

E.MATLAB/SIMULINK MODEL

DTC block is the main element of the simulink has flux and torque hysteresis block, toque and flux calculator block, switching control block and switching table block. For the estimation of the motor flux d-q components and electromagnetic torque, the torque and flux calculator blocks are used. The flux and torque hysteresis block has three-level hysteresis controller block and two level hysteresis controller for the toque control and flux control respectively. For the proper selection of voltage vector the switching table has look-up tables in it working according to the output of the flux and torque hysteresis comparison. Inverter commutation frequency is limited Switching control block.

The motor parameters used for simulation are shown below:

MOTOR PARAMETERS	
Stator Resistance	1.405 Ω
Rotor Resistance	1.395 Ω
Stator self inductance	0.00583 H
Rotor self inductance	0.00583 H
Motor Moment of Inertia	0.0131 kg-m^2
Damping Factor	0.002985 N-m-s
Motor Power	5.4 HP
Speed	1430 rpm
No. of poles	4
Voltage	400 V
Frequency	50 Hz

Table 5. Motor Parameters used in Simulation

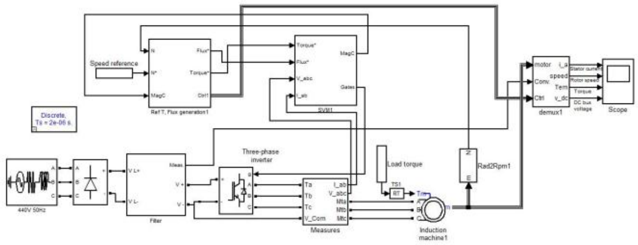

Figure 5. Simulink Model of Direct Torque Control

The control system block diagram shown in Figure 1 has been simulated for Induction Motor in the MATLAB/Simulink as shown in Figure 5.

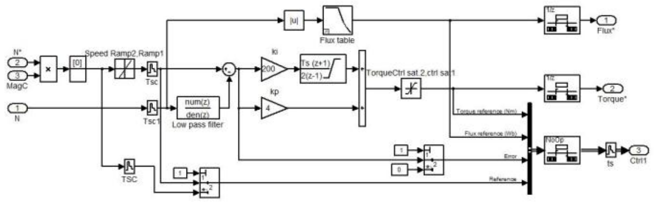

Figure 6. Simulink Model of PI Controller in DTC

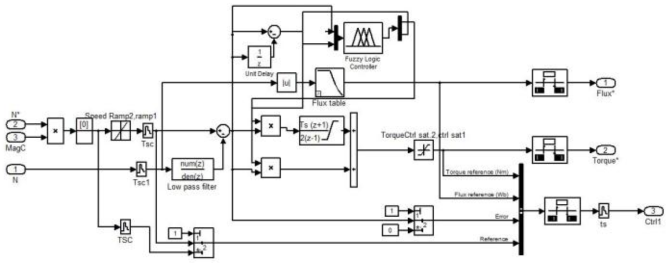

Figure 7. Simulink Model of Fuzzy tuned PI Controller in DTC

Simulink Model of PI Controller and Fuzzy tuned PI Controller in DTC is shown in Figure 6 and Figure 7 respectively.

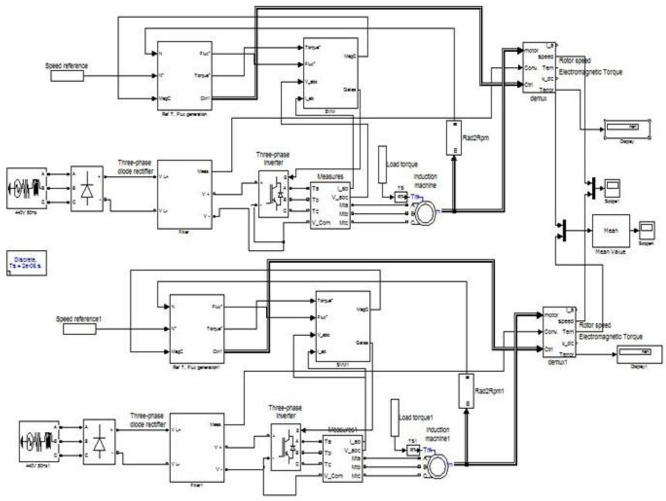

Figure 8. Combined simulation block of PI and Fuzzy tuned PI Controller

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 05, May-2016

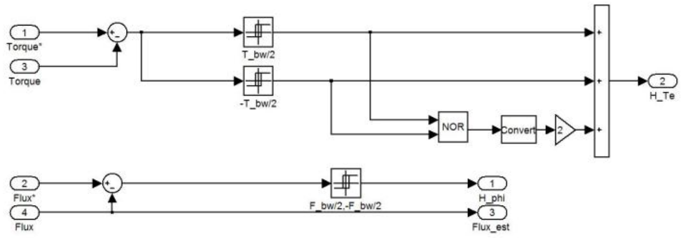

Figure 9. Flux and Torque Hysteresis

Figure 9 shows Flux and Torque hysteresis block in MATLAB. A double layer flux and a three layer torque hysteresis block are used here.

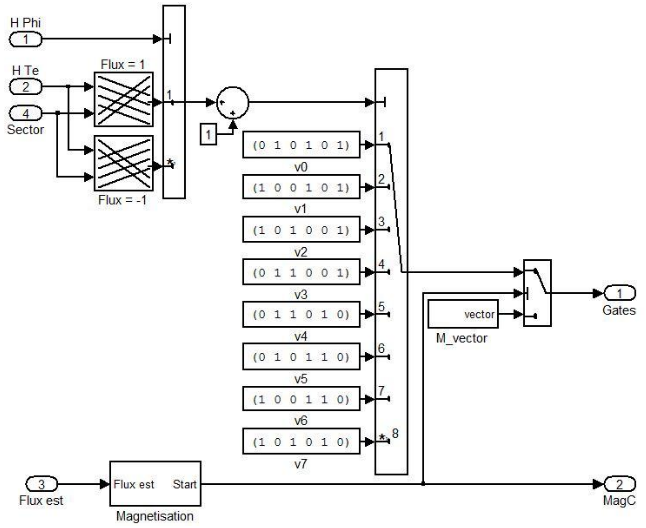

Figure 10. Voltage vector selection block

The torque and flux values are estimated are compared with the reference values , the error is compared in hysteresis comparator and the output of the comparators together with the flux sector are together employed in the switching table to determine the appropriate voltage vector as shown in Figure 10. The vector selected from switching table is then applied to the Voltage source inverter (VSI).

IV. SIMULATION RESULTS AND OUTCOMES OF STUDY

Simulation output of PI Based Speed Regulator

PI control is one of conventional control methods used along with Direct Torque Control to achieve better control in speed of Induction Motor. The simulation output of PI controller with load torque is given in Figure 11 given below.

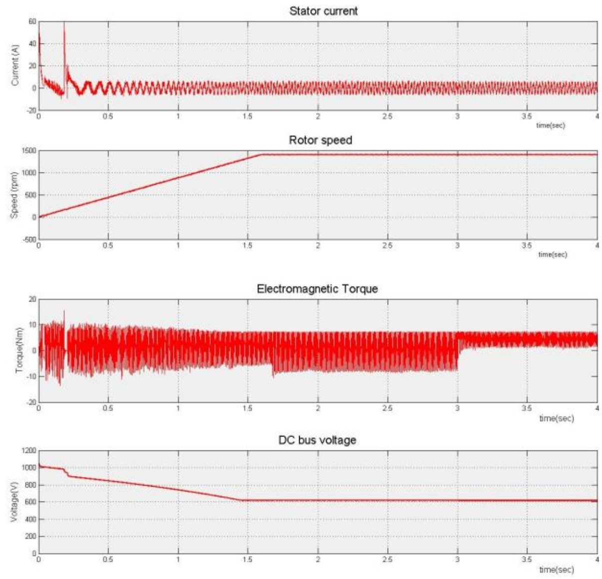

Figure 11. Simulink Output of PI Controller in DTC

Simulation output of Fuzzy tuned PI Based Speed Regulator

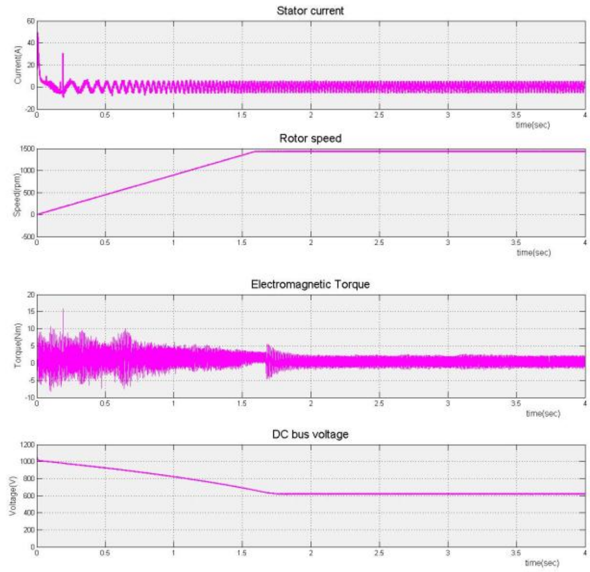

Figure 12. Simulink Output of Fuzzy tuned PI Controller in DTC

A Fuzzy controller design is based on intuition and simulation. The Simulation output of a Fuzzy tuned PI regulator is shown in Figure 12. For different values of motor speed and current, the values reducing torque and flux ripple is found out. These values composed a training set that is used to extract the truth table. The shapes of Membership Functions are refined through simulation and testing.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 05, May-2016

Comparison of Simulation output

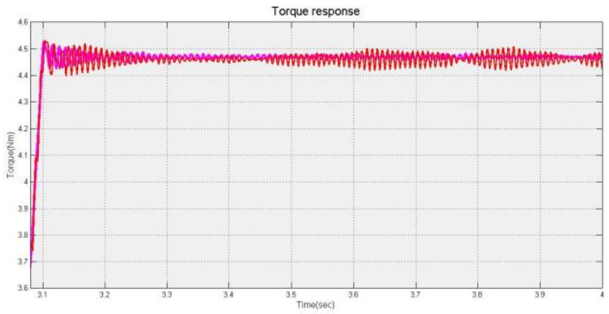

Figure 13. Comparison of Torque response

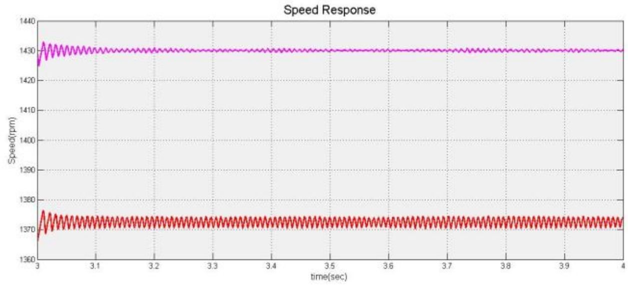

Figure 14. Comparison of Speed response

The Figures 13 and 14 gives a clear comparison between Speed performance and Torque pulsation in a PI based and Fuzzy tuned PI based speed regulators. It is clear from the output that the Fuzzy tuned PI based regulator give better performance compared to conventional PI based regulator.

V. COMPARISON OF SIMULATION RESULTS

The simulation output shows the comparison between PI and Fuzzy Tuned PI Speed Regulator. The table 6 shows the comparison of output in PI and Fuzzy tuned PI control.

Parameter	PI	9 RULE FLC
Settling time for no load and ref speed	1.6 sec	1.4 sec
Settling time for step change in load	1.8 sec	1.5 sec
Torque ripple	7-8 Nm	4-5 Nm

Table 6. Comparison of PI and Fuzzy tuned PI Controller

VI. CONCLUSION

DTC is used for efficient management of torque and flux without varying motor parameters and load value. In this method,

1. Flux and torque will be controlled by inverter voltage vector in VSI
2. It has got good dynamic performance
3. It has got fast torque response
4. The switching commands of inverter are derived from look-up table, simplifying the control system and also decreasing the processing time not like a PWM modulator employed in vector control.

By using PI and Fuzzy speed regulators, Speed performance is improved and torque ripples will be reduced.Also,on comparing the simulation output with PI and Fuzzy tuned PI based mostly speed regulators, it is seen that torque ripples are reduced and speed performance is best in Fuzzy tuned PI speed regulators

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