Advanced Control of Direct Torque Control of Induction Motor Drive Using Pi Based Fuzzy Logic Controller

Raghava Reddy. R, P. Ram Kishore Kumar Reddy

Abstract*—*A Variable-Frequency Drive is a type of adjustable-speed drive used in Electro-Mechanical drive systems to control the AC motor speed and torque by varying motor input frequency and voltage. Variable-Frequency Drives are used in applications ranging from small appliances to the largest of mine mill drives and compressors. Over the last four decades, Power Electronics technology has reduced Variable-Frequency Drive cost and size and has improved performance through advances in semiconductor switching devices, drive topologies, simulation and control techniques, and control hardware and software. 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 method to control the Variable Frequency Drives. 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. The work of this project is to study, evaluate and compare the technique of the conventional DTC and DTC-FLC applied to the induction machines through MATLAB/simulink..

Index Terms*— *Induction Motor Drive, Direct Torque Control (DTC), Fuzzy Logic Controllers (FLC).

I. INTRODUCTION

Whenever the term Electric Motor is used, we tend to think that the speed of rotation of these machines are totally controlled only by the applied voltage and frequency of the source current. But the speed of rotation of an Electrical Machine can be controlled precisely also by implementing the concept of drive. The main advantage of this concept is, the motion control is easily optimized with the help of drive. In very simple words, the systems which controls the motion of the electrical machines, are known as Electrical Drives. A typical drive system is assembled with a Electric Motor (may be several) and a sophisticated control system that controls the rotation of the motor shaft. Now a days, this control can be done easily with the help of software. So, the controlling becomes more and more accurate and this concept of drive also provides the ease of use. The Adjustable Speed Drives (ADS) are generally used in industry. In most drives AC motors are applied. The standard in those drives are Induction Motors (IM). Previously, DC machines were preferred for variable speed drives. However, DC motors have disadvantages of higher cost, higher rotor inertia and maintenance problem with Commutator and brushes. In addition they cannot operate in dirty and explosive environments. The AC motors do not have the disadvantages of DC machines. Therefore, in last three decades the DC motors are progressively replaced by AC drives. The responsible for those result are development of modern semiconductor devices, especially power Insulated Gate Bipolar Transistor (IGBT) and Digital Signal Processor (DSP) technologies. The most economical IM speed control methods are realized by using frequency converters. This drive system is widely used in large number of industrial and domestic applications like factories, transportation systems, textile mills, fans, pumps, motors, robots etc.

Then after invention of power electronics components and scalar control method like Variable Frequency Drive (VFD) 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.

Direct Torque Control (DTC) is one method used in variable frequency drives to control the torque (and thus finally the speed) of three-phase AC electric motors. This involves calculating an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor. 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. 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 transistors of the variable frequency drive are turned off and on in such a way that the flux and torque errors will return in their tolerant bands as fast as possible[6],[7]. A general classification of the variable frequency IM control methods is presented in Fig.1

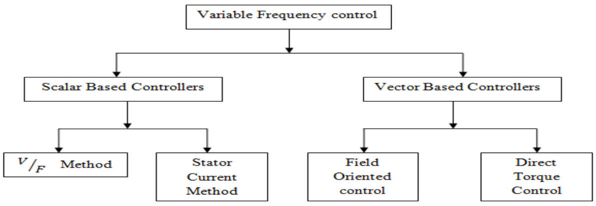

Fig 1 General Classification of Induction Motor Control Methods

It is very important to control the speed of Induction Motors in industrial and engineering applications. Efficient control strategies are used for reducing operation cost too[1]. Speed control techniques of Induction Motors can be broadly classified into two types – Scalar Control and Vector Control.

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Scalar Control involves controlling the magnitude of Voltage or Frequency of the Induction Motor, where as the Vector Control involves not only the magnitude of Voltage or Frequency but also instantaneous positions of Voltages, Currents and Flux[2].

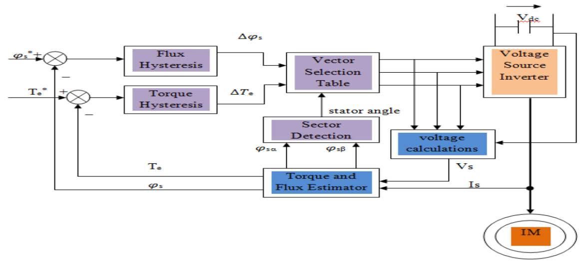

Fig 2 Basic DTC Schematic Control

II. MATHEMATICAL MODELING OF INDUCTION MOTOR:

Before going to analyze the any motor, it is very much important to obtain the machine in terms of equivalent mathematical equations. Traditional per phase equivalent circuit has been widely used in steady state analysis and design of induction motor. The dynamics considers the instantaneous effects of varying voltage/currents, stator frequency, and torque disturbance. The dynamic model of the induction motor is derived by using a two-phase motor in direct and quadrature axes. This approach is desirable because of the conceptual simplicity obtained with two sets of windings, one on the stator and the other in the rotor. The equivalence between the three phase and two phase machine models is derived from simple observation, and this approach is suitable for extending it to model an n-phase machine by means of a two phase machine.

The concept of power invariance is introduced; the power must be equal in the three-phase machine and its equivalent two-phase model. Derivations for electromagnetic torque involving the currents and flux linkages are given. The differential equations describing the induction motor are nonlinear. For stability and controller design studies, it is important to linearize the machine equations around a steady state operating point to obtain small signal equations. In or adjustable speed drive, the machine normally constituted as element within a feedback loop, and therefore its transient behavior has to be taken into consideration. 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.

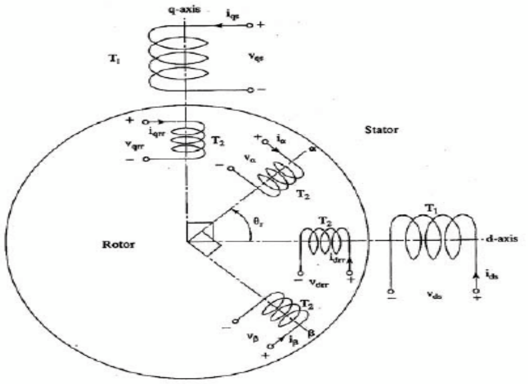

Fig 1 Two-phase equivalent diagram of induction motor The two-phase equivalent diagram of three-phase induction motor with stator and rotor windings referred to d – q axes are shown in Fig 3.2. The winding are spaced by 90^o electrical and rotor winding at α , is at an angle θ_r from the stator d-axis. It is assumed that the d axis is leading the q axis for clockwise direction of rotation of the rotor.

$$\left.\begin{aligned} v_{ds} &= R_s i_{ds} + p\Psi_{ds} \\ v_{qs} &= R_s i_{qs} + p\Psi_{qs} \\ v_{dr} &= R_r i_{dr} + \omega_r \Psi_{qr} + p\Psi_{dr} \\ v_{qr} &= R_r i_{qr} - \omega_r \Psi_{dr} + p\Psi_{qr} \end{aligned}\right\} \quad (1)$$

$$\Psi_{ds} = \int (v_{ds} - R_s i_{ds}) dt \quad (2)$$

$$\Psi_{qs} = \int (v_{qs} - R_s i_{qs}) dt \quad (3)$$

$$T_e = \frac{3}{2} P \left(\varphi_{ds}^s i_{qs}^s - \varphi_{qs}^s i_{ds}^s \right) \quad (4)$$

III. DIRECT TORQUE CONTROL (DTC)

The Direct Torque Control (DTC) is one method used in variable frequency drives to control the torque (and thus finally the speed) of three-phase AC electric motors[6]. This involves calculating an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor. 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. 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 transistors of the variable frequency drive are turned off and on in such a way that the flux and torque errors will return in their tolerant bands as fast as possible[5].

In a Direct Torque Controlled (DTC) Induction Motor Drive supplied by a voltage source inverter, it is possible to control directly the stator flux linkage ψ_s and the electromagnetic torque by the selection of an optimum inverter voltage vector. The selection of the voltage vector of the voltage source inverter is made to restrict the flux and torque error within their respective flux and torque hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant. DTC enables both quick torque response in the transient operation.

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

$$T_e = \frac{3}{2} P (\varphi_s \times i_s) \quad (5)$$

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 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.

$$\frac{d\varphi_s}{dt} = V_s \quad \text{or}$$

$$\Delta\varphi_s = V_s . \Delta t \quad (6)$$

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.

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3.1 Voltage Source Inverter

Based on the switching condition of switches S1 to S6 the output voltage is varied and that voltage is appeared at the motor terminals. The respective voltages is shown in below table 4.1

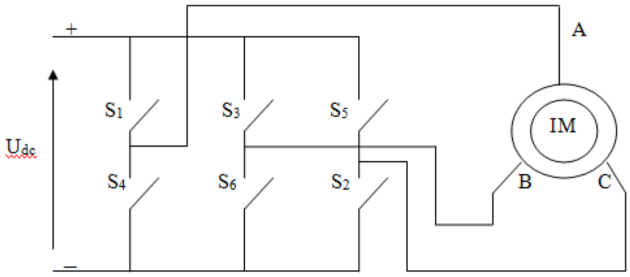

Fig.4 Diagram of voltage source Inverter

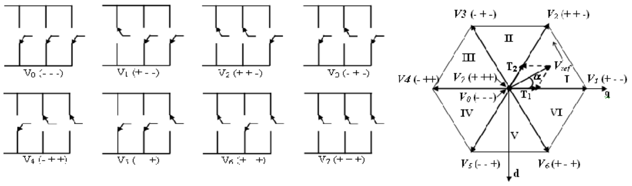

Fig.5 a) Switching states of VSI b) space vector diagram

Table 4.1 Switching States of VSI

S_1	S_2	S_3	S_4	S_5	S_6	$S_a(t)$	$S_b(t)$	$S_c(t)$
OFF	ON	OFF	ON	OFF	ON	0	0	0
ON	OFF	OFF	ON	OFF	ON	1	0	0
ON	OFF	ON	OFF	OFF	ON	1	1	0
OFF	ON	ON	OFF	OFF	ON	0	1	0
OFF	ON	ON	OFF	ON	OFF	0	1	1
OFF	ON	OFF	ON	ON	OFF	0	0	1
ON	OFF	OFF	ON	ON	OFF	1	0	1
ON	OFF	ON	OFF	ON	OFF	1	1	1

3.2 Torque Estimator

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[10].

$$T_e = \frac{3}{2} P \left(\varphi_{ds}^{s} i_{qs}^{s} - \varphi_{qs}^{s} i_{ds}^{s} \right) \tag{7}$$

$$\varphi_{ds}^{s} = \int (V_{ds} - R_s i_{ds}) dt \tag{8}$$

$$\varphi_{qs}^{s} = \int (V_{qs} - R_s i_{qs}) dt \tag{9}$$

$$T_e = \frac{3}{2} P \left(i_{qs}^{s} \int (V_{ds} - R_s i_{ds}) dt - i_{ds}^{s} \int (V_{qs} - R_s i_{qs}) dt \right) \tag{10}$$

3.3 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 4.12 and 4.13. The commonly used method of flux estimation are discussed[10].

$$\Psi_{dr}^{s} = \widehat{\Psi}_r \cos\theta_e \tag{11}$$

$$\Psi_{qr}^{s} = \widehat{\Psi}_r \sin\theta_e \tag{12}$$

$$\cos\theta_e = \frac{\Psi_{dr}^{s}}{\widehat{\Psi}_r} \quad ; \quad \sin\theta_e = \frac{\Psi_{qr}^{s}}{\widehat{\Psi}_r} \tag{13}$$

$$\Psi_r = \sqrt{{\Psi_{dr}^{s}}^2 + {\Psi_{qr}^{s}}^2} \tag{14}$$

IV. FUZZY LOGIC CONTROLLER

Fuzzy control is a control method based on fuzzy logic. Fuzzy logic can be described simply as computing with words rather than numbers; fuzzy control can be described simply as control with sentences rather than equations. A fuzzy controller can include empirical rules, and that is especially useful in operator controlled plants. Fuzzy logic controller (FLC) is capable of improving its performance in the control of a nonlinear system whose dynamics are unknown or uncertain. Fuzzy controller is able to improve its performance without having to identify a model of the plant. Fuzzy control is similar to the classic closed-loop control approaches but differs in that it substitutes imprecise, symbolic notions for precise numeric measures. The fuzzy controller takes input values from the real world. These crisp input values are mapped to the linguistic values through the membership functions in the fuzzification step. A set of rules that emulates the decision making process of the human expert controlling the system is then applied using certain inference mechanisms to determine the output. Finally, the output is mapped into crisp control actions required in practical applications in the de-fuzzification step. They are non-precise variables that often convey a surprising amount of information. Usually, linguistic variables hold values that are uniformly distributed (µ) between 0 and 1, depending on the relevance of a context dependent linguistic term[3].

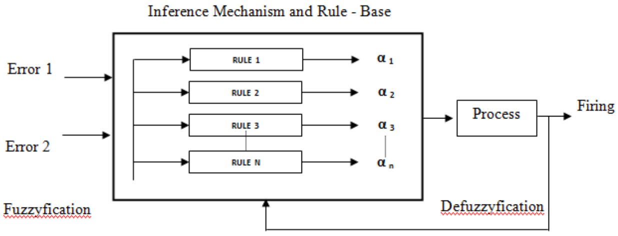

Fig.6 Basic FLC

1-**Fuzzification**, which converts controller inputs into information that the inference mechanism can easily uses to

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activate and apply rules.

2-**Rule-Base**, (a set of If-Then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.

3-**Inference Mechanism**, (also called an "inference engine" or "fuzzy inference" module), which emulates the expert's decision making in interpreting and applying knowledge about how best to control the system

4-**Defuzzification Interface**, which converts the conclusions of the inference mechanism into actual inputs for the process.

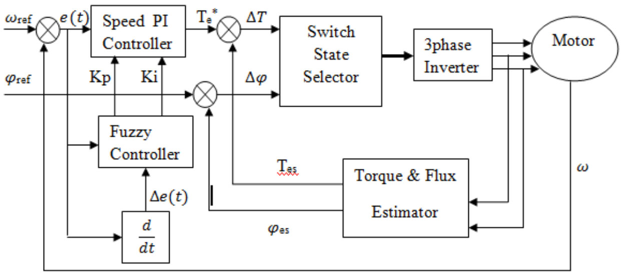

Fig.7 Block diagram of PI based FLC speed control

To easily handle the large values of error and change in error and reduce the computation time so as to achieve faster control action, the inputs and output are normalized[4].

$$E = e(t) = N_{ref} - N_{act}$$

$$CE = e(t) - e(t-1)$$

Table 2 Linguistic Term For Error

Linguistic term	Symbol
Negative Large	NL
Negative Medium	NM
Nagative Small	NS
Zero Error	ZE
Positive Small	PS
Positive Meduim	PM
Positive Large	PL

Table 3 Linguistic Term For Change Of Error

Linguistic term	Symbol
Negative	N
Zero	Z
Positive	p

Table 4 Fuzzy Control Linguistic Roles For Proportional Gain

e(t) $\Delta e(t)$	NL	NM	NS	ZE	PS	PM	PL
N	L	M	S	M	S	M	L
Z	L	M	L	Z	L	M	L
P	L	M	L	Z	L	M	L

Table 5 Fuzzy Control Linguistic Roles For Integral Gain

e(t) $\Delta e(t)$	NL	NM	NS	ZE	PS	PM	PL
N	Z	S	M	L	M	S	Z
Z	Z	S	M	L	M	S	Z
P	Z	M	L	L	L	M	Z

The fuzzy rule R_i is defined as R_i : if $e(t) = A_i$ and $\Delta e(t) = B_i$, then $K_p = C_i$ and $K_i = D_i$ where variable A_i, B_i, C_i and D_i are fuzzy subsets of speed error, change in speed error, proportional coefficient, and integral coefficient, respectively i= 1 to 21, there are 21 reason rule. Mamdhani's reason method is adopted to get the defuzzification output value can be acquired by using linear transform to the output value.

V. SIMULATION RESULTS

Fig. 6.1 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 6.1 is constructed according to the block diagram of DTC of Induction Motor (Fig 4.1). 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 speed regulator, the reference speed and the actual speed is compared and the error in speed is passed through the controller and thus the reference torque T_e^* is obtained. the speed regulators for both the conventional control and fuzzy logic control of DTC of Induction Motor is Simulated. 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^* .

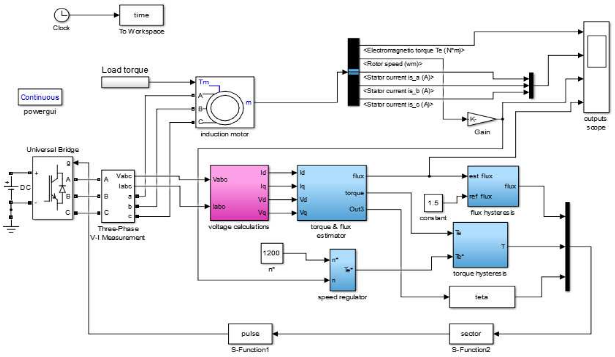

Fig.8 Simulation Diagram

The simulation of Direct Torque Control of induction motor is done by using MATLAB-SIMULINK. The results for conventional DTC and Fuzzy Logic Control of Induction Motor are shown in Fig 9 and Fig 10 respectively.

From the Fig 9, the ripples are observed in currents, speed and torque. In conventional DTC-PI, the values of proportional gain and integral gain is fixed where as in DTC-FLC, the gain values are adopted from online and thus reduces the ripples in torque, speed and currents. The simulation result support that the DTC with Fuzzy control (Fig 10) has better performance. Simulation results validate that the effectiveness of the method and show that good speed regulation can be achieved.

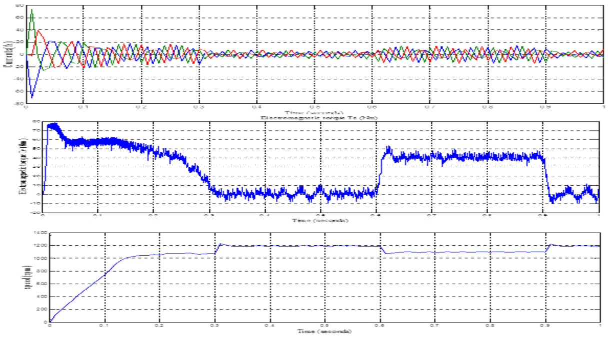

Fig 9 Simualtion Results of Conventional DTC-PI

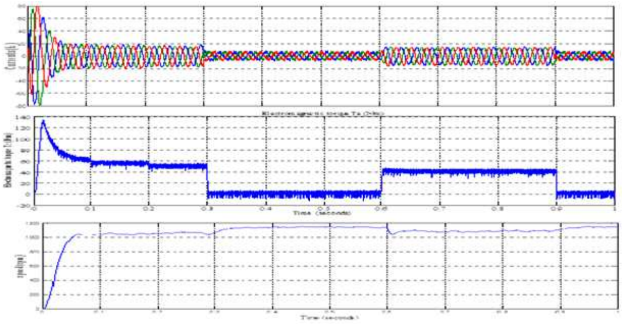

Fig 10 Simualtion Results of DTC-FLC

VI. CONCLUSIONS

For variable speed control of Induction Motor, the controllers called scalar and vector controllers are proposed. Scalar Control is good for steady state response and it is based on the relationships valid in the steady state conditions of magnitude and frequency of voltage, current, and flux linkage. Vector Control is based on relationships valid for dynamic states, not only magnitude but also instantenious positions of voltage and flux. The vector control acts on the posotion of the space vectors and provides their correct orientation both in steady and dynamic states. The decoupled control of torque and flux is obtained by Direct Torque Control (DTC) thus the torque and flux are controlled separetely.The conventional DTC using PI based , there are some disadventages, such as variable switching frequency, high ripples in currents and torque and low oparaeting conditionds. These drawbacks are overcomed by using Fuzzy Logic Controllers.Fuzzy Logic control is one of the controller in the artificial inteliigence technique. A Fuzzy control rule look- up table to overcome the above drawbacks. According to the speed error and change in speed error, the proportional gain values are adjusted online, and thus ripples are reduced. The simulation result support that the DTC with Fuzzy control has better performance.It is concluded from results that conventional DTC controlled Induction Motor drive cannot meet the Fuzzy Controlled Induction Motor for ripple reduction.

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