Performance of Direct Torque Controlled Induction Motor Drive by Fuzzy Logic Controller

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Abstract: In this paper, fuzzy logic controller (FLC) is proposed in speed and torque control loop of the Direct Torque Controlled Induction motor (IM). Direct torque controller (DTC) is used to achieve good transient response with latent features an induction motor drive. The conventional DTC produces Flux/Torque ripple and variable switching frequency. The FLC is proposed to achieve smooth ripple free torque and speed performance. In this proposed technique, the speed error and change in speed error are processed through the FLC. The proposed fuzzy logic controller calculates the appropriate inputs variables for the DTC loop using logic variables. The FLC produces the reference torque for the torque control loop. The electromagnetic torque is controlled to control the speed of the induction motor. Space Vector Pulse Width Modulation (SVPWM) is used to generate gate pulses for the three-phase Voltage Source Inverter with constant switching frequency. The proposed FLC and conventional PI controller system are modeled in MATLAB/SIMULINK and simulation results are compared in terms of torque ripples and current harmonics. The effectiveness of the proposed algorithms is investigated by hardware implementation by PIC microcontroller. Total Harmonic Distortion (THD) analysis for load current is also carried out in this paper

Keywords: Induction motor drive, Direct torque control, PI controller, Fuzzy logic controller, SVPWM, Microcontroller, THD

1. INTRODUCTION

In basic DTC scheme PI controllers, coordinate transformations, current controllers and PWM signal generators are eliminated. From the switching table, Voltage Source Inverters are not able to produce a precise voltage vector for making zero torque ripples. (Allirani et al., 2012) proposed a torque hysteresis band with variable magnitude FLC to reduce the torque and flux error. At low speed, the performance was improved by using the fuzzy logic controller to minimize the flux and torque ripples. Compared to conventional DTC, inverter duty ratio control method give good steady state torque output and low torque ripple. Fuzzy logic control has been used for implementing the duty ratio control.

Space vector pulse width modulation technique has been used to reduce flux and torque in direct torque controlled Induction motor drives (Abdesselem, 2014; Anjana and Jebin, 2013). Direct torque controlled induction motor drive using space vector modulation is implemented (Muchande et al., 2013) by Texas Instrument's Piccolo series TMS320F28069 digital signal controller.

Three efficient optimization algorithms, namely Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Golden Search (GS) have been employed to reduce power loss in direct torque controlled induction motor drive system (KeertiRai et al., 2013). The performance assessment has been done and compared with one another technique based on loss minimization. In this work, for a suitable optimal efficiency operation of the IM drive has been done by recalculation of optimized flux component of current based on the selected optimization techniques. Improvement in efficiency of IM drive operation has been achieved and the core loss of the drive system was reduced by all the three algorithms. Compared to the other two techniques PSO based IM drive operation has the advantages of fast response and high accuracy. PSO based energy optimization scheme adjust flux component of current to reduce the system loss. Moreover, these three approaches do not create parameter variation and no need for additional hardware for implementation.

(Vahid and Amir, 2013) presented Optimization method for an inverter-driven Induction Motor (IM) drive using a modified Particle Swarm Optimization (PSO). At any operating point, optimal output frequency and voltage of the drive has been exerted to achieve the maximum efficiency of the motor. Modified PSO algorithm has been used to find the optimal amplitude and frequency of the excitation voltage. In this method, multiple global best particles are selected from the swarm. Compared with the traditional PSO, Multi-Best Particle Swarm Optimization (MBPS) converges faster, and in the same operation time accomplishes to a more accurate approximation of the solution

In modern control theory, various mathematical models are available for induction motor based on newly developed techniques. Compared to DC motors the vector controlled IM in the self-governing torque and flux control mechanism provides them in their energetic performance. In (Oualid et al., 2014, Rosli et al., 2011; D.Archana et al., 2012) DTC with a three-level inverter (NPC structure) has been presented to reduce torque ripple instead of the two-level inverter and a PI-fuzzy controller instead of the classic PI controller. Conventional PI speed controller has been replaced by the FLC in order to improve the speed response. This will provide higher the power range of the drive system which is sufficiently robust and intelligent for real-time applications.

(Jamal et al., 2015) proposed a rule-based Mamdani type fuzzy logic controller to closed-loop control of Induction Motor drive. According to the parameters of the motor model, membership functions are chosen and the motor model has been designed for the new operating point. The actual velocity of an induction motor has been compared with a reference velocity and the mistake was given through (FLC) and their outputs control the focal ratio to regulate the speed of IM and to get better torque response (Naveena et al., 2015). (Anmol et al., 2015; Yugal et al., 2016) developed a scalar control technique using fuzzy logic algorithm for the induction motor speed control. The fuzzy logic technique was applied (Suraj et al., 2017) to reduce torque ripples in DTC induction motor drive. The main drawback of DTC is its high torque ripples. In this approach, the two hysteresis controllers are changed by two fuzzy logic controllers. Due to the angular error accumulation in the velocity integration process speed estimation without angular correction block revealed poor control quality. At the same time, the transition processes were tracked by unwanted nonlinear characteristics. To overcome this problem the sensorless induction motor control system has been proposed in (Solodkiy et al., 2017) based on the adaptive rotor speed observer. In this continuous angle correction in coordinate transformation has been done based on a phase-locked loop. The method has a simple model implementation for real object adjustment. The speed observer has been implemented using the original method of correction at angular error computations on the basis of phase mismatch determination of the stator current.

An adaptive neuro-fuzzy interference system (ANFIS) based speed control has been proposed in (Chandra and Maruthes, 2014) for the induction motor drive system. In (Chandra and Maruthes, 2017), CUCKOO search algorithm has been used to train the data and test the ANFIS to offer appropriate electromagnetic torque which in turn alter the inverter switching states. The performance of this CS based ANFIS speed controller has been compared with PI, fuzzy and ANFIS speed controllers. Rotor speed, torque, settling time, peak overshoot and steady state error has been analyzed.

A novel algorithm of predictive torque control (PTC) has been proposed (Amiri et al., 2018) for induction motor based on discrete space vector modulation (SVM) scheme. The number of voltage vectors was increased by the DSVM system and it has been valued in the PTC method. This PTC-DSVM gave low sampling frequency. But, the high number of virtual vectors increased computational burden considerably. To overcome this problem, the DTC switching table has been presented in which the number of admissible voltage vectors was reduced. At any switching frequency, PTC-DSVM has the same performance as conventional PTC but the sampling frequency is three times lesser. The low sampling frequency algorithm makes it feasible for industries to employ low-cost hardware or execute a high computational analysis.

(Mohammad and Mahdi, 2013) presented flexible-joint robots with decentralized direct adaptive fuzzy logic technique. The Lyapunov stability based fuzzy logic controller has been used for the whole robotic system which includes the robot, actuators and its motors. This technique employs simple voltage control instead of complex torque control. Direct torque control for dual two level inverter fed induction motor drive is proposed (Toufouti et al., 2009) with neuro-fuzzy based space voltage modulation. An adaptive neuro-fuzzy inference system generates the reference voltage for the inverter using space vector modulation. The flux and torque ripples have been reduced to a considerable value and constant switching frequency is obtained by this technique. In (Ameur et al., 2013), the sectors of switching table are modified and the hysteresis band and stator resistance estimation are employed with fuzzy logic controller in direct torque. The overall performance of the controller has been improved by this modified approach. (Mohsen et al., 2014) proposed fuzzy logic based direct torque and flux control technique with space vector modulation for Line-Start Permanent Magnet Synchronous Motor (LSPMSM). The improved performance of the proposed method shows that the LSPMSM can be used instead of induction motor and permanent magnet synchronous motor in electrical drive applications.

In this proposed system, the better characteristics of Direct torque controller (DTC) is combined with Fuzzy Logic Controller (FLC) to produce an excellent dynamic performance of the Induction Motor (IM) with reduced torque ripples. The DTC of IM with space vector modulation is discussed in section 2. The implementation of proposed FLC is given in section 4. The simulation results of the IM drive system for both PI and proposed FLC scheme are presented in section 5.1. The hardware implementation of the proposed technique is presented and the performance of the proposed system is compared with the PI controller in section 5.2 for both simulation and experimental results.

2. DIRECT TORQUE CONTROLLED INDUCTION MOTOR DRIVE

The proposed FLC based DTC of Induction motor drive system is given in Fig.1. The dynamic performance of Induction motor is evaluated by using its mathematical model. The machine parameters are affected by the dynamic performance of IM.

The torque of the three-phase AC motors is controlled by Direct Torque Control (DTC) in variable speed drives. The instantaneous values of the stator voltage and current are used to estimate the electromagnetic torque and stator flux from the mathematical model of the drive system and these quantities are compared with their reference values. The errors generated are used in the FLC controller and further in Space Vector Pulse Width Modulation (SVPWM) generator to select the appropriate switching states for the Voltage Source Inverter (VSI) so that flux and torque errors are limited within the prescribed band limits. The FLC system is proposed in this work to increase the system speed of the transient response and to reduce the harmonic current.

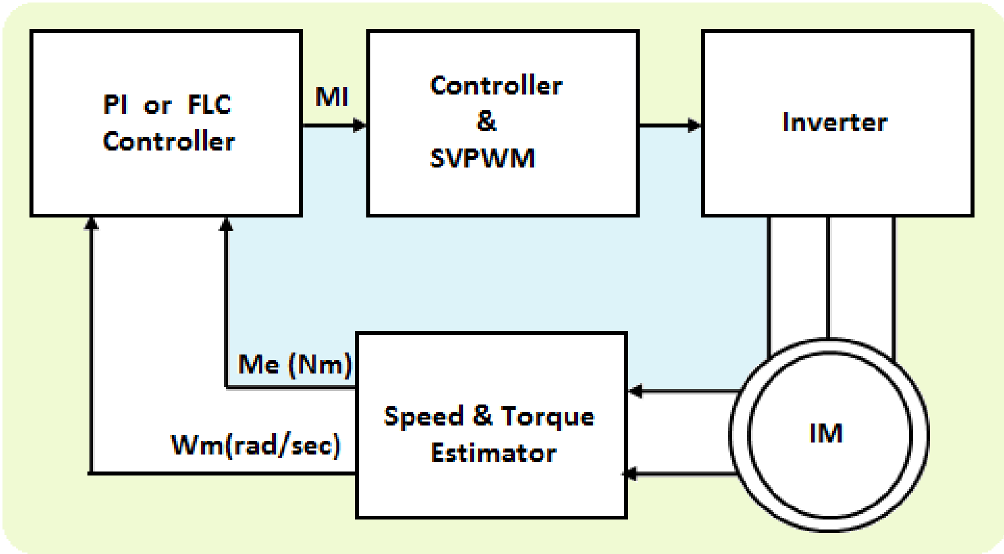


Fig. 1. Direct torque controlled Induction Motor.

The three-phase voltage and current quantities of IM are obtained from the inverter output terminals. These three phase variables are converted into two-phase d–q variables by the park's transformation.

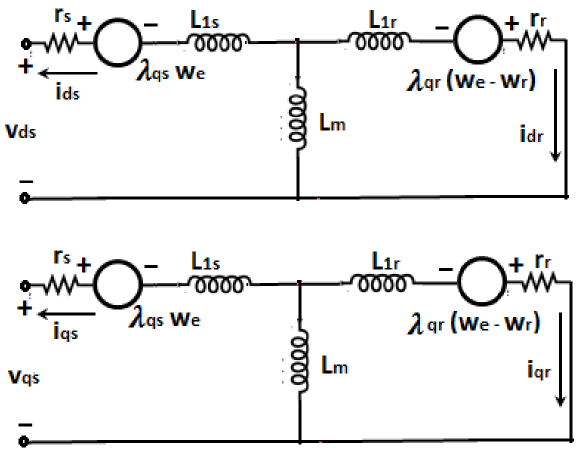


Fig. 2. Equivalent circuit of the IM in the d-q coordinate frame.

The equivalent circuit of the IM is modeled in Fig. 2. The stator voltage equations in d–q coordinate frame are given in (1) to (4).

$$V_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} \qquad (1)$$

$$V_{qs} = r_s i_{qs} + \frac{d\lambda_{qs}}{dt} \qquad (2)$$

$$V_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt} + \lambda_{qr}\omega_r \qquad (3)$$

$$V_{qs} = r_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \lambda_{dr}\omega_r \qquad (4)$$

Stator and rotor fluxes in d–q coordinate frame are given in (5) & (6).

$$\lambda_{d\alpha} = \lambda_{dr} = i_{dr}L_{1r} + i_{ds}L_{1s} \qquad (5)$$

$$\psi_{qs} = \psi_{qr} = i_{qr}L_{1r} + i_{qs}L_{1s} \qquad (6)$$

Stator Flux in d–q coordinate frame is estimated using (7), (8) & (9).

$$\lambda_{ds} = \int (V_{ds} - r_s i_{ds})\, dt \qquad (7)$$

$$\lambda_{qs} = \int (V_{qs} - r_s i_{qs})\, dt \qquad (8)$$

$$|\lambda_s| = \sqrt{(\lambda_{ds}^2 + \lambda_{qs}^2)} \qquad (9)$$

Rotor angle and electromagnetic torque are estimated using (10) & (11).

$$\theta = atan\frac{\lambda_{ds}}{\lambda_{qs}} \qquad (10)$$

$$T_e = (3P/4).(\lambda_{ds} i_{qs} - \Psi_{qs} i_{ds}) \qquad (11)$$

The electromagnetic torque and stator flux of induction motor is calculated using the d-q components of stator voltage and stator current. The estimated electromagnetic torque and flux quantities are compared with their reference values generated by the FLC for the production of the reference voltage. This reference voltage is used to generate SVPWM gate signals for the Voltage Source Inverter (VSI). Finally, VSI controls the speed and torque of the IM in accordance with their reference values.

Space vector PWM technique has been introduced to overcome the drawbacks associated with the other PWM scheme which consider the inverter as a single unit. The most feasible PWM technique used for the six switches three-phase inverter is SVPWM. In recent days, the SVPWM technique is frequently used for the control of high power ac motor drives. The gate pulses given to the three-phase inverter are in such a way that they reduce the harmonic content in input current and voltages applied to the three-phase ac motor. Therefore dc link voltage is effectively utilized and switching losses are reduced by avoiding unwanted switching. Another noticeable advantage of SVPWM techniques is constant switching frequency and it can be regulated based on the drive requirement.

Space vector contains a rotating constant magnitude constant frequency vectors which are obtained from their three-phase sinusoidal quantities. There are six non-zero vectors and two zero vectors in SVPWM technique. The reference voltage is obtained from the adjacent two non-zero vectors and two zero vectors. The steps involved in SPVWM are the calculation of reference voltage and sector number, calculation of time duration for each switching states and each switch.

3. PI CONTROLLER

The simulation diagram for the PI controller is given in Fig. 3. The PI controller is the combination of the proportional, integral controller. The main aim of the controller is to make the system to follow the reference value. Proportional controller changes the gain of the system based on the error signal. The PI control parameters of speed and torque for Fig. 3 are given as follows.

PI Controller Parameters

Speed control		
1.	*Kp*	16.2160
2.	*Ki*	2.8096
Torque control		
1.	*Kp*	0.6757
2.	*Ki*	0.1171

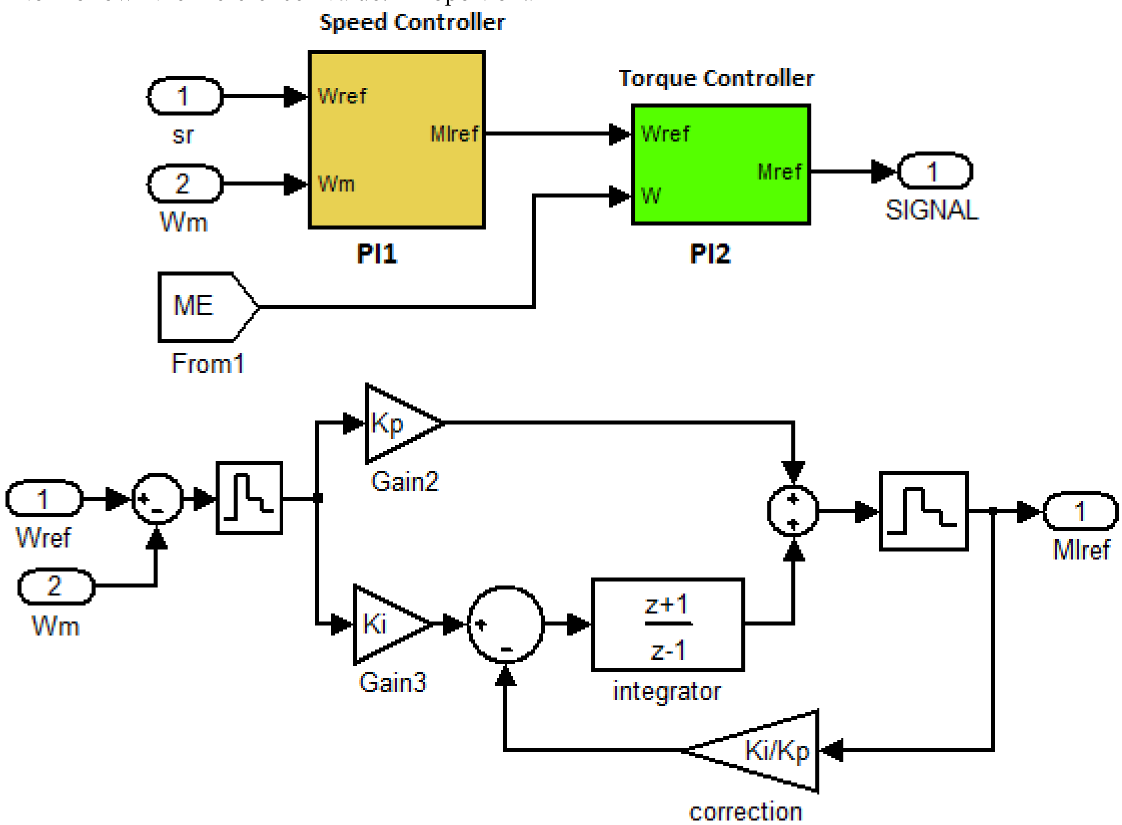


Fig. 3. PI controller.

The reduced steady state error and improved system accuracy is achieved by the application of PI controller. The drawback of the system is the low system stability. The integral controller integrates the error signal and makes the response close to the reference. The transfer function of the PI controller is given as (12).

$$u(t) = K_p \left[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right] \tag{12}$$

Where,

K_p = Proportional gain

$Ki = K_p/T_i$ Integral gain

$u(t)$ - Input signal to the plant

$e(t)$ - error signal

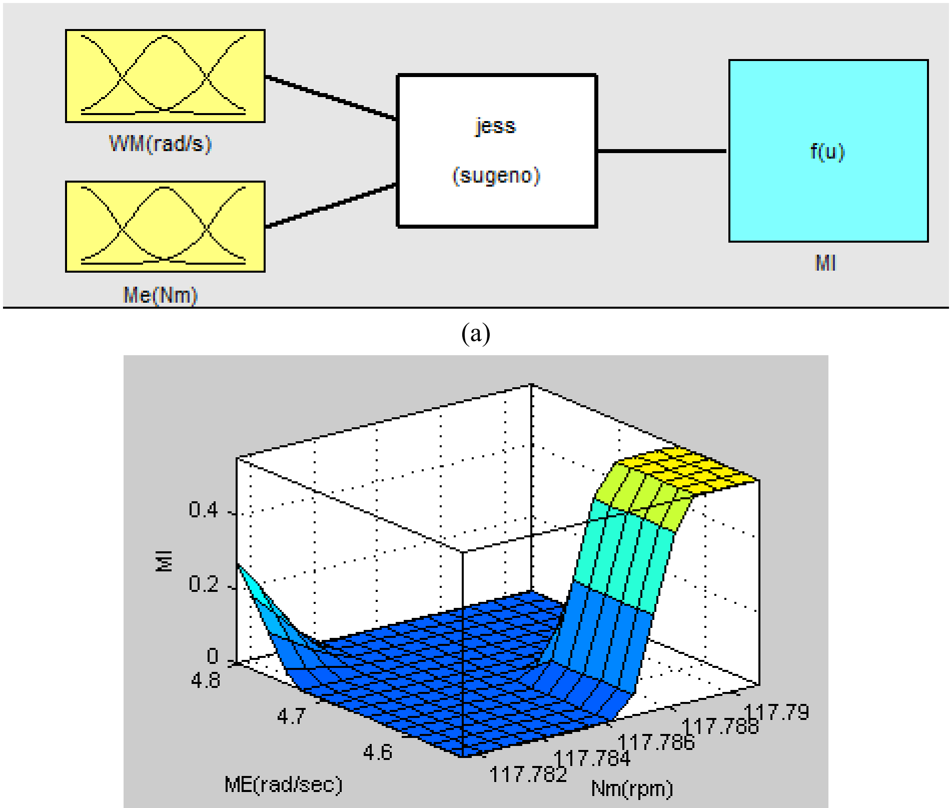
$e(t) = r(t) - y(t)$

$r(t)$ - reference signal

4. FUZZY RULE-BASED DTC SYSTEM

The gain of traditional PI controllers is constant. For change in system parameters and environment condition, PI controllers will not produce effective compensation. PI controller needs more settling time for quick variation of the system state. So the response will be too slow. It is very difficult to find the exact values of proportional, integral and differential gain of the PI controller. To overcome these complications Fuzzy Logic Controller (FLC) is used which will give improved system performance compared to the conventional PI control techniques. Fuzzy logic control (FLC) does not require any mathematical model of the system. FLC involves only linguistic control variables instead of crisp variables and somewhat it decides like a human brain for the control of the system. With the implementation of the fuzzy logic controller, adaptive speed control can be achieved by accurate tracking of the motor speed to the reference speed. The performance of the FLC is decided by the selection of membership function for the input variable, output variable, and fuzzy if-then rules. The selected membership functions must enclose the whole universe of discourse. The slight change in the input variable has to be considered so that the membership functions are overlapped.

In Fig. 4., the control structure of the proposed FLC is easily described. There are two input state variables and one control variable in the FLC. The input variables are speed error (*Wm (rad/s)*) and electromagnetic torque error (*Me* (*Nm*)). The speed error and torque error are determined from their reference values and estimated values.



(a)

(b)

Fig. 4. (a) FLC-membership function (b) surface view.

The output variable is the reference voltage vector for the pulse generator. Based on the fuzzy logic control output, the gate signals are generated by SVPWM generator for controlling the inverter output voltage and frequency. Membership function decides the operation of FLC. Here triangular membership function is used. FLC is incorporated for both speed and torque control in DTC of Induction motor drive system. Without the knowledge of the exact model of the given system, FLC can be easily designed. The fuzzy rule-based system is achieved by three stages like Fuzzification, inference engine and defuzzification.

4.1. Fuzzification

The fuzzy membership function values are allotted to the five linguistic variables such as Negative Big (NB), Negative Small (*NS*), Zero (*ZE*), Positive Big (PB) and Positive Small (PS). In this proposed system the motor speed (Wm) and electromagnetic torque (Me) are selected as input variables of the system. Here Mamdani type fuzzy model is designed in the fuzzy logic controller. The input membership functions are shown in fig.4 the gbellmf type of membership functions are selected to control the system. The range of each membership function is taking by nominal speed and nominal electromagnetic torque.

Table 1. Fuzzy rule base.

Error	Change in Error				
	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	NB
PB	ZE	PS	PS	PB	NB

4.2. Inference engine

This stage mostly contains the fuzzy rule base. Evaluation of the input variable is done in this rule base only. In this stage first, the input variables are fuzzified and fed through the inference engine and finally rule base is applied. The fuzzy rule base is given in Table 1. From the defined if-then rule base fuzzy output variables are identified.

4.3. Defuzzification

After identification of linguistic fuzzy output variables, the defuzzification is done because to obtain the controlled output variable. The centroid defuzzification method is exercised in the proposed approach. The output membership functions values are allotted to the five linguistic variables such as Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Big (PB) and Positive Small (PS). The output of the fuzzy logic controller is the stator reference voltage. This voltage is processed through the SVPWM to generate the firing pulses to the inverter to control the speed of the induction motor in relation to the reference speed.

5. RESULTS AND DISCUSSION

5.1 Simulation Results

The proposed fuzzy rule-based DTC approach has been executed in MATLAB/SIMULINK. The torque-speed control performance of the proposed fuzzy logic control technique has been tested on the induction motor with rating as shown in Table 2. The performance of the proposed control technique was compared with the PI controlled Induction motor drive. Fig. 5 illustrates the Simulink model of the proposed PI and FLC spped-torque control system.

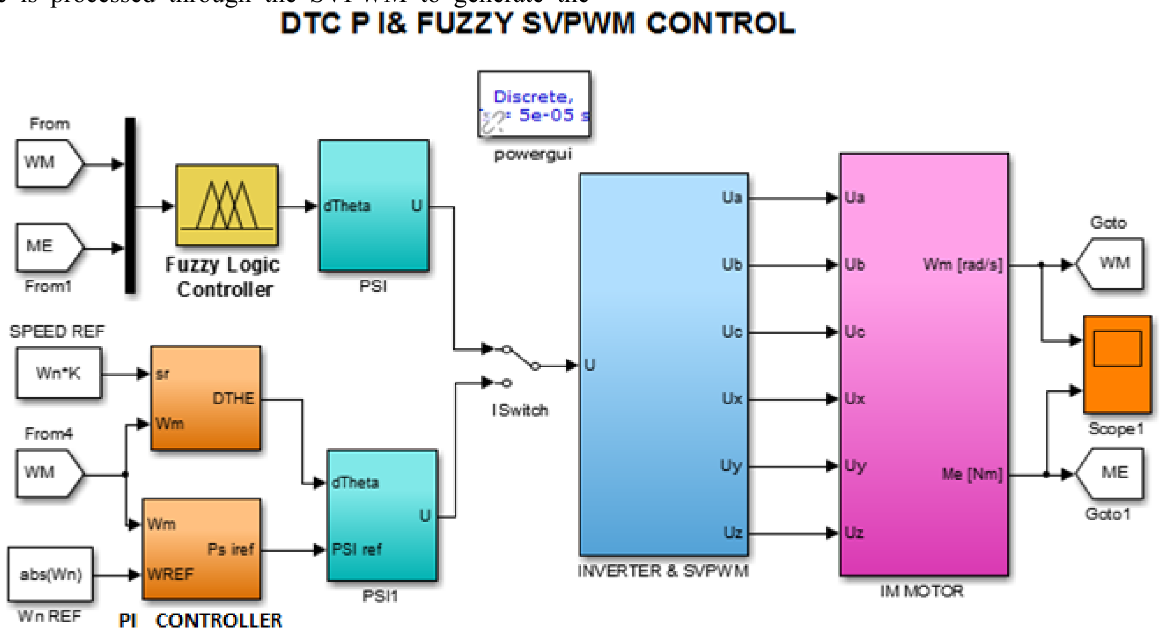


Fig. 5. Simulink Model of PI and FLC Speed Control System.

Table 2. Motor Parameter.

1	Stator resistance(Rs)	11.6	Ohm
2	Rotor Resistance(Rr)	10.4	Ohm
3	Frequency	50	Hz
4	Rated Power(P)	750	W
5	Speed(Nm)	1410	RPM
6	Phase Voltage(Uph)	220	Volts

The proposed PI and FLC control schemes are simulated with MATLAB/Simulink for the Induction motor drive system. The setpoint is described by the dynamic response of the IM when the modulated torque setpoint duration of [0 0.3333 0.6666 and 1 second] and Modulated torque [0 0.5*4.74 1*4.74]. The variations in time of main electrical and mechanical variables are obtained. It explains that the proposed drive system gives good speed control performance with reduced settling time, reduced oscillation in the waveforms and low steady-state error.

The ripple content in torque for modulated input, PI controlled and FLC controlled scheme are given in Fig. 6. Fig. 6 (c) reveals that torque ripples get reduced by the use of a fuzzy logic controller.

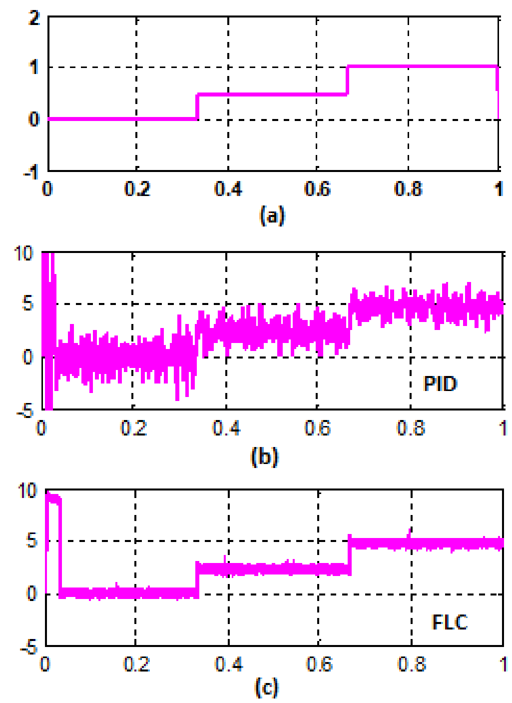


Fig. 6. Torque ripples (a) Modulated input (b) PI (c) FLC.

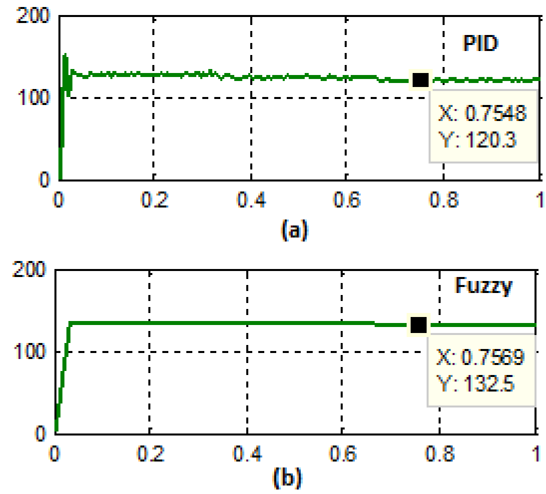


Fig. 7. Speeds (a) PI (b) FLC.

The speed response of the proposed drive is given in Fig. 7. From the Fig. 7(b) it is clear that the speed error is reduced and accurate speed tracking is also achieved by FLC. The steady-state value cannot be approached by using the PI controller. So that, the presented FLC speed-torque control algorithm is more efficient than the PI controller.

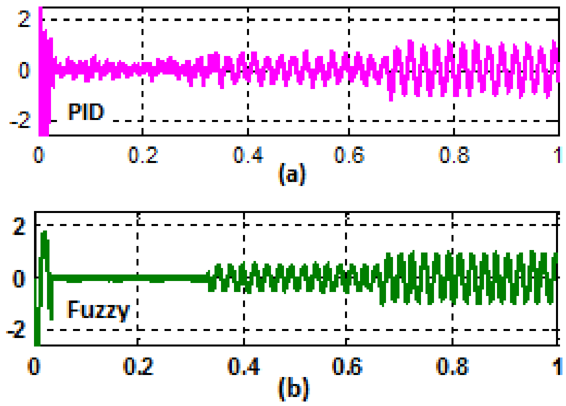


Fig. 8. Single phase current (a) PI (b) FLC.

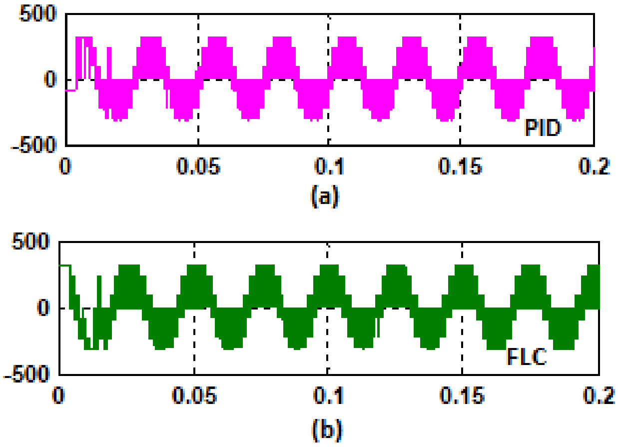


Fig. 9. Voltages (a) PI (b) FLC.

Fig. 8 and 9 show the stator current and voltage waveforms for the both PI and Fuzzy Logic Controller. Fig. 10 shows the load current waveform. These waveforms illustrate that the distortions are reduced for FLC based drive.

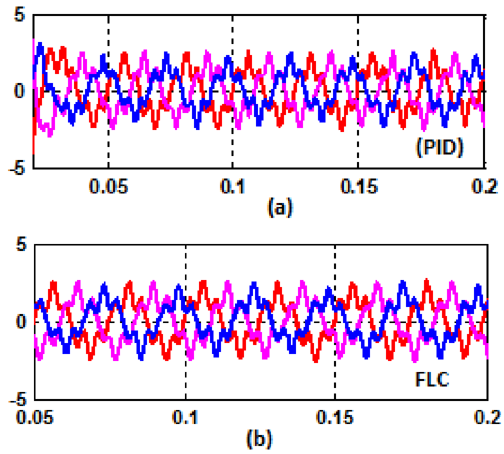


Fig. 10. Three phase Load current (a) PI (b) FLC.

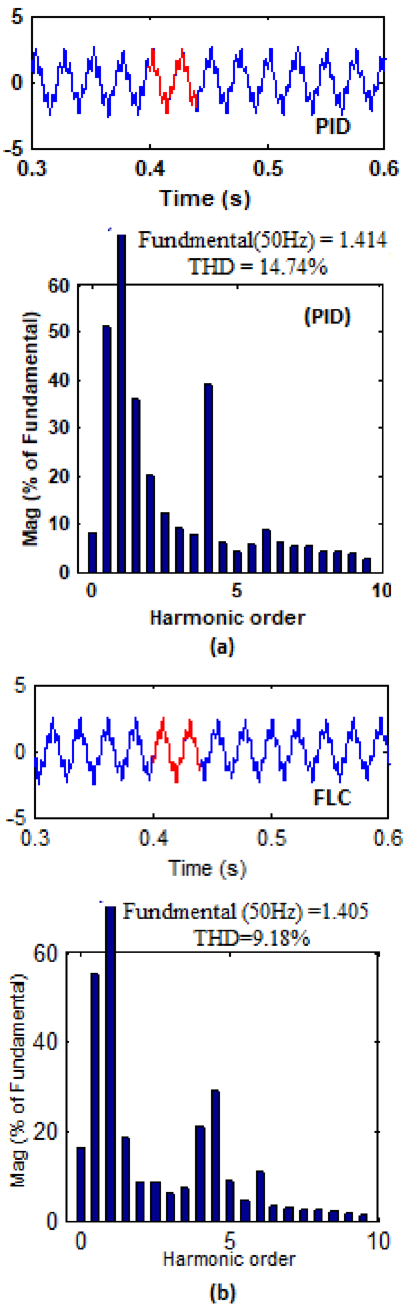


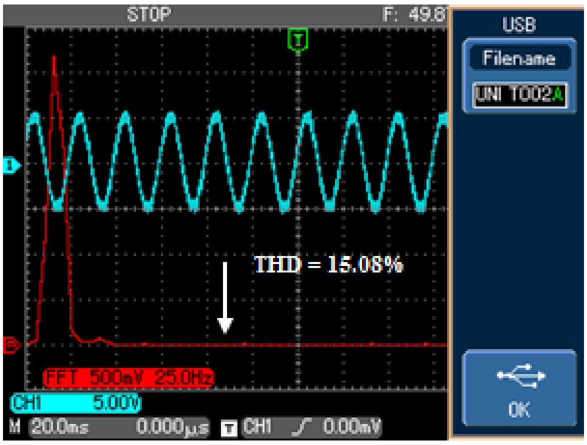
Fig. 11. Current THD %(a) PI (b) FLC.

Fig. 11 explains the fundamental current wave and harmonic spectrum for PI and FLC scheme.

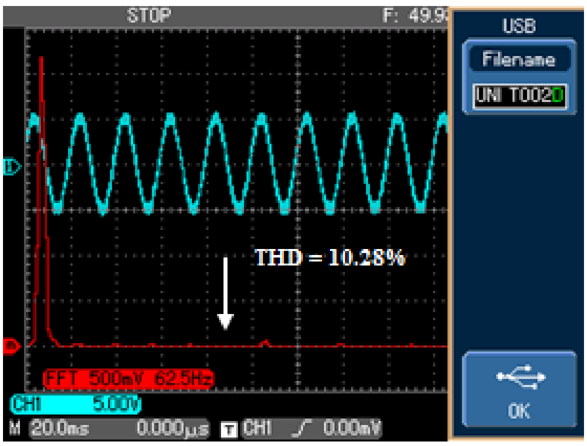
5.2 Experimental verification

The simulation results were validated experimentally by using the suitable hardware setup which is built with the PIC microcontroller. The experimental set up of squirrel cage IM (750W/220V) drive is constituted as exhibited in Fig.12.The power electronics converter circuit includes a rectifier and an IGBT based voltage source inverter. This converter circuit conserves the valuable characteristics of the classical DTC like simple technique which is designed in a stationary frame. Generally, the inclusion of FLC and SVM in DTC drive control scheme solves the most conventional DTC drawbacks.

Fig. 12. Presentation of the experimental setup.



(a)



(b)

Fig. 13. Stator current (a) PI (b) Fuzzy.

5.3 Comparison of THD % for PI and FLC system

Table 3. THD% value.

Controller	Simulation result in THD%	Experimental result in THD%
PI	14.74	15.08
FLC	9.18	10.28

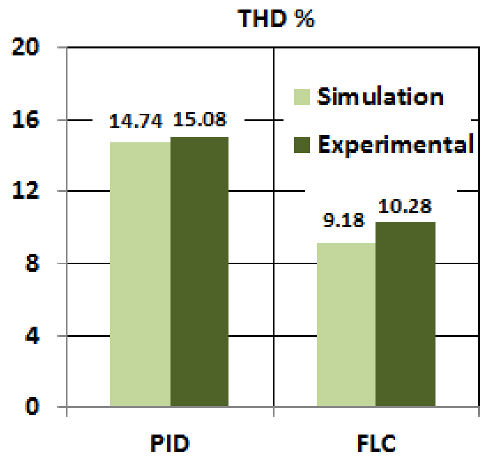


Fig. 14. Comparison chart of THD value.

The proposed studied system is tested in the laboratory and the photograph of the experimental setup that includes the microcontroller, UNI –T four channels DSO, IGBT based inverter. DSO is used to take the current waveform with their harmonic spectrum which is presented in Fig.13 and Table 3. In the Fig.14, the comparative performances of the proposed Fuzzy controller and PI controller are described for both simulation and experimental results. The behavior of the modified direct torque control technique for induction motor control has been examined as a comparative study by the hardware implementation using real-time interface linked to the microcontroller.

6. CONCLUSION

The performances of control have been investigated as a comparative study by an experimental implementation using real-time interface linked to a PIC16F877A microcontroller platform. In the present work, fuzzy rule-based Direct Torque Control of the induction motor is proposed. The characteristics of the proposed algorithm were appraised and implemented on a 750W/220V induction motor drive system. The mathematical model of the three-phase induction motor has been developed with differential equations governing stator voltage, stator flux, and torque. The PI controller and the FLC algorithm have been developed for the proposed drive system. The simulation and hardware results for PI and FLC control technique have been analyzed and compared. From the performance comparative result, it is decided that the proposed fuzzy logic control technique is better than the conventional PI control technique in both simulation and excremental analysis.

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