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Comparative Analysis of Fuzzy Logic with Reduced Rule Base and PI Controller for A Direct Torque Controlled Induction Motor Drive

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Abstract

Induction motors are most commonly used in the industry. Therefore, many control methods have been developed to obtain accurate speed trajectory and adequate torque values for induction motors. In this study, Simulation studies are realized for speed control of direct torque controlled (DTC) induction motor via MATLAB/Simulink. Firstly, a fuzzy logic controller (FLC) with reduced rule base is developed using MATLAB/Simulink Fuzzy Logic Toolbox. Then, the conventional PI controller and FLC have been applied, to speed control unit of induction motor. Simulation studies are implemented for both of the controllers under same conditions. The results obtained from conventional PI controller and FLC are analyzed and compared. According to obtained simulation results, it is observed that FLC provides better speed and torque response than PI controller.

1. Introduction

DC motors have high performance in terms of dynamic behaviour and their control is simple. Because its flux and torque can be controlled independently. However, DC motors have certain disadvantages due to the existence of the commutators and brushes. Nowadays, induction motors are extensively used in industrial application. Induction motors have complex mathematical models with high degree of nonlinear differential equations including speed and time dependent parameters. However, they are simple, rugged, inexpensive and available at all power ratings. Therefore, the speed control of induction motor is more important to achieve maximum torque and efficiency [1-5]. By the rapid development of microprocessor, power semiconductor technologies and various intelligent control algorithm, controlling methods of induction motors have been improved. In the recent years, researchs about induction motors which are common in industrial systems due to some important advantages are focused on vector based high performans control methods such as field orientation control (FOC) and Direct torque control (DTC) [1-7].

FOC principles were firstly presented by Blaschke [4] and Hasse [5]. FOC of induction motors are based on control principle of DC motors. DC motors have high performance in terms of dynamic behaviour and their control is simple. Armature and excited winding currents of self-excited DC motors can be independently controlled because they are vertical to each other. There isn't such case in induction motors. Made studies on induction motors showed that these motors could be controlled such as DC motors if three-phase variables are converted to dq-axis and dq-axis currents are controlled. Vector control methods which are done transform of axis have been developed. Flux and torque of induction motors can be independently controlled. Thus induction motors can adequately be used for variable speed drive applications [1-4].

DTC were firstly presented by Depenbrock [6] and Takahashi [7]. DTC method has simple structure and the main advantages of DTC are absence of complex coordinate transformations and current regulator systems. In the DTC method, the flux and torque of the motor are controlled directly using the flux and torque errors which are processed in two different hysteresis controllers (torque and flux). Optimum switching table depending on flux and torque hysteresis controller outputs is used to control of inverter switches in order to provide rapid flux and torque response. However, because of the hysteresis controllers, the DTC has disadvantage like high torque ripple. In the recent years, FLC has found many applications. Fuzzy logic is a technique, improved by Zadeh [8] and it provides human-like behavior for control system. İt is widely used because FLC make possible to control nonlinear, uncertain systems even in the case where no mathematical model is available for the controlled system [8-14]. This paper presents comparison of fuzzy logic with reduced rule base and PI controller on speed control of DTC induction motor. The performance of the proposed controller has been researched and compared with PI controller.

2. Direct Torque Control

DTC design is very simple and practicable. It consists of three parts such as DTC controller, torque and flux calculator and VSI. In principle, the DTC method selects one of the inverter's six voltage vectors and two zero vectors in order to keep the stator flux and torque within a hysteresis band around the demand flux and torque magnitudes [6-7]. The torque produced by the induction motor can be expressed as shown below:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left|\overline{\psi_r}\right|\left|\overline{\psi_s}\right|\sin\alpha \qquad (1)$$

Where, α is angle between the rotor flux and the stator flux vectors. ψ_r is the rotor flux magnitude and ψ_s is the stator flux magnitude. P is the pairs of poles, L_m is mutual inductance and L_r is rotor inductance. This equation (1) shows the torque is dependent on the stator flux magnitude, rotor flux magnitude and the phase. angle between the stator and rotor flux vectors. The equation of induction motor stator is given by [6]:

$$\overline{V}_s = \frac{d\psi_s}{dt} + i_s R_s \qquad (2)$$

If the stator resistance is ignored, it can be approximated as equation 3 over a short time period [6-7]:

$$\Delta\overline{\psi}_s = \overline{V}_s \Delta t \qquad (3)$$

This means that the applied voltage vector determines the change in the stator flux vector. If a voltage vector is applied to system, the stator flux changes to increase the phase angle between the stator flux and rotor flux vectors. Thus, the torque produced will increase [6-7,15].

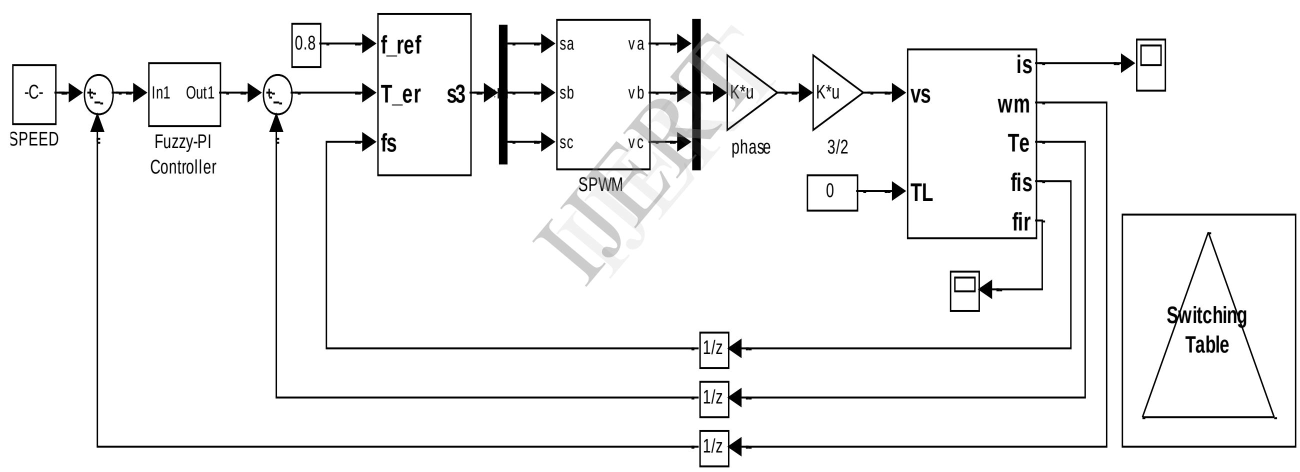

Figure 1. DTC induction motor system in MATLAB/Simulink environment

Fig. 1 shows closed loop direct torque controlled induction motor system. The closed loop DTC induction motor system is implemented in MATLAB/Simulink environment. DTC induction motor model consists of four parts such as speed control, switching table, inverter and induction motor. d-q model is used for the induction motor design. DTC blog has flux and torque within a hysteresis models. Two-level and three-level flux and torque within hysteresis band comparators are given in Fig. 2 and 3, respectively. Flux control is performed by two-level hysteresis band and three-level hysteresis band provides torque control. Outputs of the hysteresis bands are renewed in each sampling period and changing of the flux and torque are determined by these outputs.

Voltage vectors are shown in Fig. 4. Flux control output $d\psi_s$, torque control output dT_e and voltage vector of the stator flux are determined a Switching Look-up Table as shown in Table 1. In DTC method, stator flux and torque are estimated to compare with references of the flux and torque values by aid of stator current, voltage and stator resistance. The obtained flux and torque errors are applied to the hysteresis layers. In these hysteresis layers, flux and torque bandwidth are defined. Afterwards, the amount of deflection is determined and the most appropriate voltage vectors are selected to apply to the inverter using Switching Look-up Table.

If a torque increment is required then dT_e equals to +1, if a torque reduction is required then dT_e equals to -1 and if no change in the torque is required then dT_e equals to 0. If a stator flux increment is required then $d\psi_s$ is equals to +1, if a stator flux reduction is required then $d\psi_s$ equals to 0. In this way, the flux and torque control is implemented.

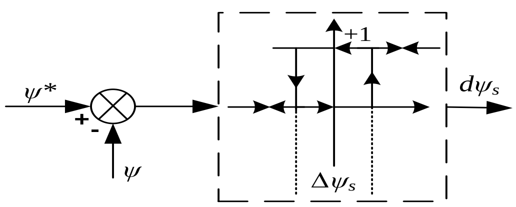

Figure 2. Two-level flux hysteresis comparator

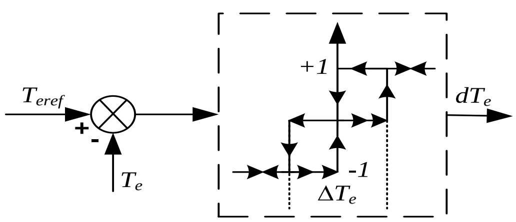

Figure 3. Three-level torque hysteresis comparator

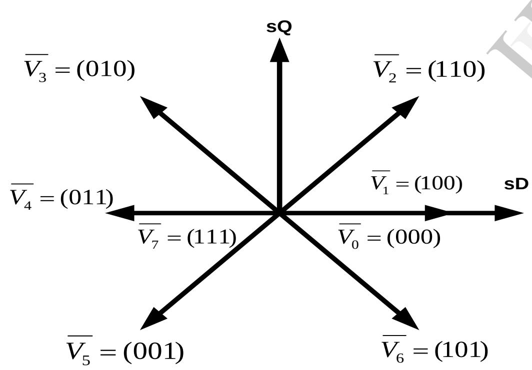

Figure 4. Voltage vectors

Table 1. Switching Look-up Table

Flux (ψ)	Torque (T_e)	SECTORS					
		S1	S2	S3	S4	S5	S6
ψ=1	Te=1	V2	V3	V4	V5	V6	V1
	Te=-1	V6	V1	V2	V3	V4	V5
ψ=-1	Te=1	V3	V4	V5	V6	V1	V2
	Te=-1	V5	V6	V1	V2	V3	V4

3. Fuzzy Logic Controller

In this paper, the FLC is proposed to control the speed of the motor to be constant. The proposed FLC and conventional PI controller are designed and applied to the DTC model. FLC is an appropriate method for designing nonlinear controllers via the use of heuristic information [15-17]. A FLC system allows changing the control laws in order to deal with parameter variations and disturbances. Fig. 5 shows the block diagram of fuzzy logic controller using simulation study. Where e and Δe are the input, Δu is output fuzzy variables.

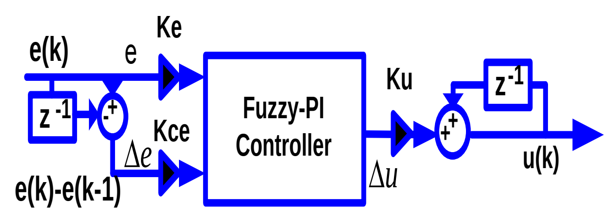

Figure 5. Block diagram of FLC

In the design of FLC, three membership functions were used for both error e(k), change of error Δe(k) and output Δu. Membership functions were constructed to represent the inputs and output value. Fig. 5 and 6 show the fuzzy sets and corresponding triangular membership function description of each signal for input and output respectively. The fuzzy sets are as follows: z = Zero, p = Positive, n = Negative. The rule base of FLC system is given in Table 2. There may be 3×3=9 possible rules in the matrix.

Table 1. Rule Base

e \ de	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

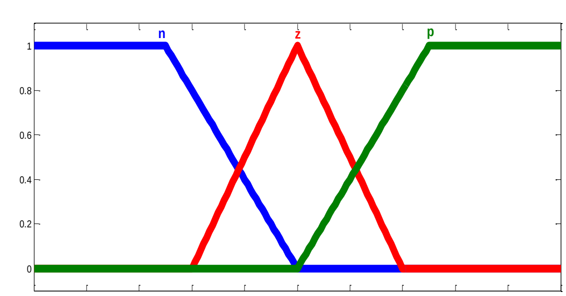

Figure 6. Membership functions for inputs and output

4. Simulation Results

The study of DTC induction motor drive with implementing fuzzy logic controller with reduced rule base and PI controller is carried out in the MATLAB/Simulink environment. The simulations are performed for different reference speeds with load of 3N-m and no-load during 1sec. The parameters of the induction motor used in the simulation are given in Table 3.

Table 3. Induction Motor Parameters

Parameters	Values
Stator resistance (R_s)	8.231Ω
Rotor resistance (R_r)	4.49Ω
Number of Poles (P)	2
Stator self-inductance (L_s)	0.599H
Rotor self-inductance (L_r)	0.599H
Moment of inertia (J)	0.0019kg-m^2
Mutual inductance (L_m)	0.5787H
Friction factor (B)	0.000263

Fig. 7 shows the speed response of the induction motor with both PI and FLC at no-load and the output torque is given in Fig. 8. As it seen in fig. 8, the reference speed is 2000 rpm. The PI controller response reaches to reference speed after 150 ms with overshoot and the FLC response reaches to steady state after nearly 78 ms without overshoot. The simulation results show the proposed FLC provides good speed response over the PI controller. The output torques controlled by proposed FLC and PI controllers is illustrated in fig. 8 and 9.

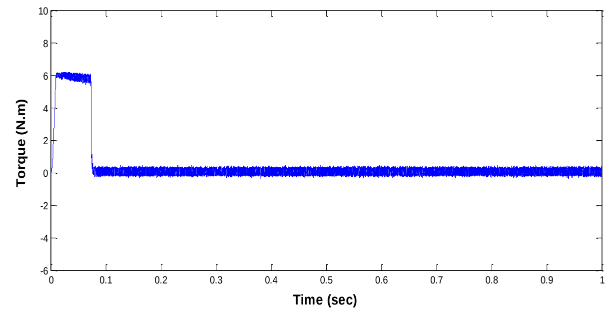

Figure 8. The output torque response(FLC)

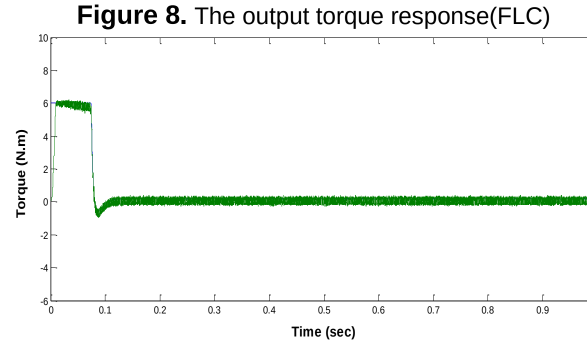

Figure 9. The output torque response(PI)

Fig. 9 demonstrates the dynamic response of the proposed control technique. Firstly, DTC induction motor starts to operate in a steady state at 1500 rpm reference speed. Then, a sudden step speed command increasing, from 1500 rpm to 2250 rpm is performed. The FLC follows the reference speed without any overshoot and steady state error. As it can be seen from the simulation results, the performance of FLC is obviously superior to that of conventional PI control for all speed change cases. The torque responses of proposed FLC and PI controllers are given in fig. 11 and 12, respectively.

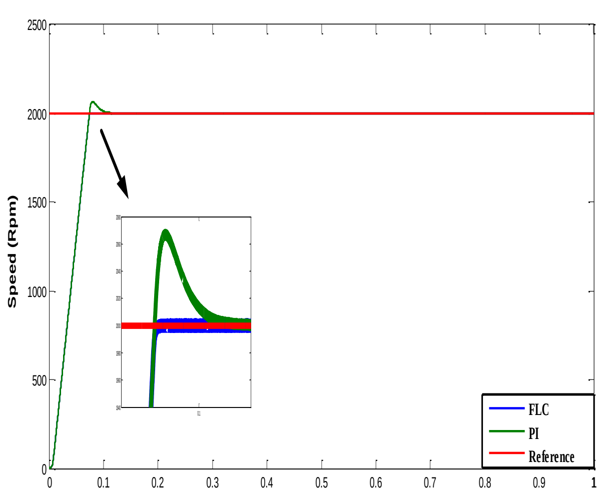

Figure 7. Speed response comparison at no-load

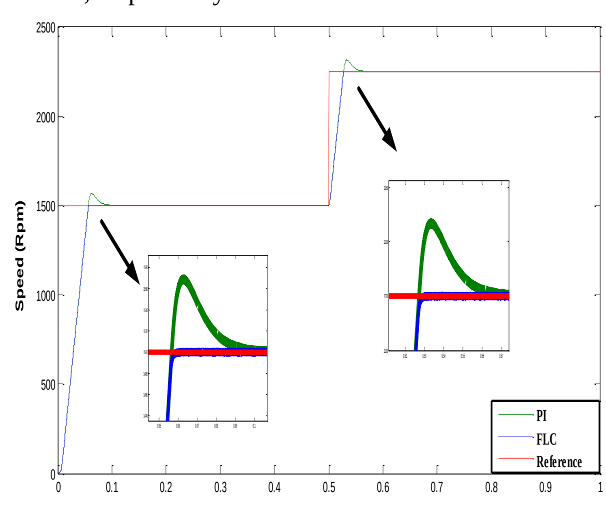

Figure 10. Speed response comparison at no-load

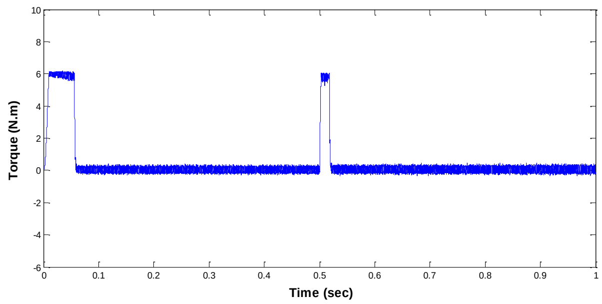

Figure 11. The output torque response(FLC)

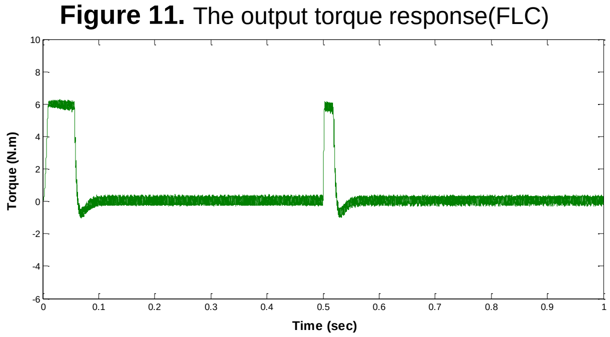

Figure 12. The output torque response(PI)

Constant speed response with load of 3N-m at 0.5sec is given in fig. 13. The speed response with proposed FLC has no overshoot and settles faster in comparison with PI controller and there is no steady-state error in the speed response. When the load is applied there is sudden dip in speed. The speed falls from reference speed of 1750 rpm to nearly 1739 rpm and it takes 5 ms to reach the reference speed. As it seen, the proposed control technique gives better performance against the conventional PI controller with respect to overshoot, rise time and response time. The torque responses of proposed FLC and PI controllers are given in fig. 14 and 15, respectively.

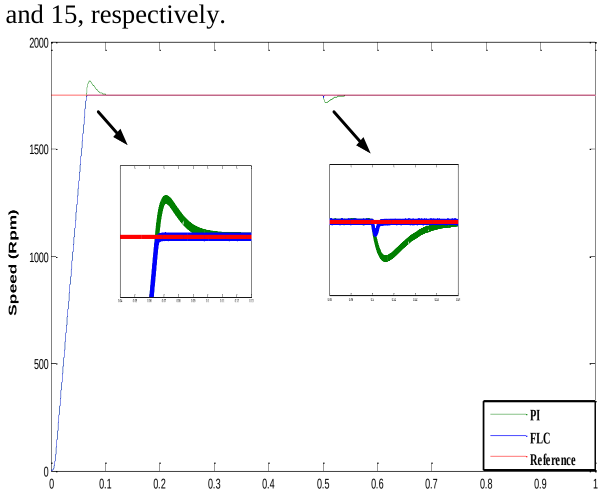

Figure 13. Speed response comparison with load

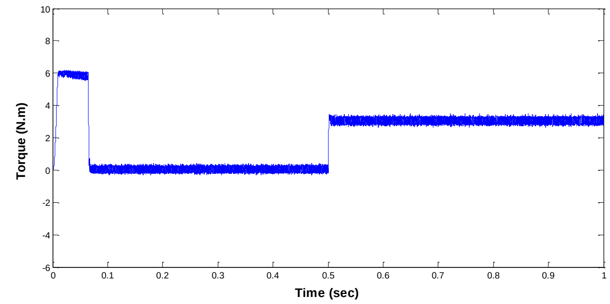

Figure 14. The output torque response(FLC)

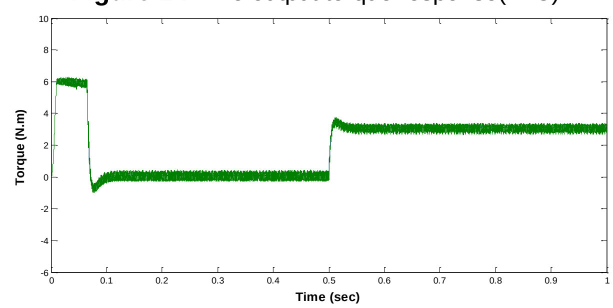

Figure 15. The output torque response(PI)

5. Conclusions

In this paper, DTC induction motor drive system is presented and speed control of the induction motor is implemented. The motor drive system is carried out in MATLAB/Simulink environment using mathematical model of d-q of the induction motor. Then, the proposed FLC have been designed for speed control loop via MATLAB/Fuzzy Logic Toolbox. Afterwards, Compared simulation results with conventional PI controller are given. The responses obtained from the simulation esults, showed that the behavior with fuzzy logic control is advantageous compared with PI control for all speed change cases. In addition, the fuzzy logic controller with reduced rule base is easily designed and don't need the mathematical model of system to be controlled. Therefore, these features of the proposed fuzzy controller make it more attractive.

6. References

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