International Journal of
Intelligent Systems and Applications in Engineering

ISSN:2147-6799 www.ijisae.org Original Research Paper

Speed Control of Direct Torque Controlled Induction Motor By using PI, Anti-Windup PI and Fuzzy Logic Controller

Hakan Açıkgöz[1*], Ö.Fatih Keçecioğlu[2], Ahmet Gani[2], Mustafa Şekkeli[2]

Received 9th March 2014, Accepted 29th September 2014

Abstract: In this study, comparison between PI controller, fuzzy logic controller (FLC) and an anti-windup PI (PI+AW) controller used for speed control with direct torque controlled induction motor is presented. Direct torque controlled induction motor drive system is implemented in MATLAB/Simulink environment and the FLC is developed using MATLAB/Fuzzy-Logic toolbox. The proposed control strategy is performed different operating conditions. Simulation results, obtained from PI controller, FLC and PI+AW controller showing the performance of the closed loop control systems, are illustrated in the paper. Simulation results show that FLC is more robust than PI and PI+AW controller against parameter variations and FLC gives better performance in terms of rise time, maximum peak overshoot and settling time.

Keywords: *Anti-windup PI controller, Direct torque control, Fuzzy logic controller, Induction motor, 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 and they need little maintenance. 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. 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 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 deals with comparison of PI, FLC and PI+AW controller on speed control of direct torque controlled induction motor. The performance of FLC has been researched and compared with PI+AW and PI controller.

The rest of this paper is organized as follows. In Section II, direct torque control scheme is given. Section III describes proposed controller design. The simulation results are given in Section IV. Conclusions are presented in Section V.

2. DIRECT TORQUE CONTROL

The induction motor model can be developed from its fundamental electrical and mechanical equations. The d-q equations of 3-phase induction motor expressed in the stationary reference frame:

$$V_{ds} = R_s i_{ds} + p\psi_{ds} \tag{1}$$

$$V_{qs} = R_s i_{qs} + p\psi_{qs} \tag{2}$$

---

[1] *Kilis 7 Aralik University, Dept. of Electrical Science, Kilis/TURKEY*
[2] *K.Maras Sutcu Imam University, Dept. of Electrical and Electronics Engineering, K.Maras/TURKEY*
** Corresponding Author: Email: hakanacikgoz@kilis.edu.tr*

$$0 = R_r i_{dr} + p\psi_{dr} - w_r \psi_{qr} \tag{3}$$

$$0 = R_r i_{qr} + p\psi_{qr} - w_r \psi_{dr} \tag{4}$$

The flux linkage equations:

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \tag{5}$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \tag{6}$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{7}$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{8}$$

Electromagnetic torque in the stationary reference frame is given as:

$$T_e = \frac{3}{2}\frac{P}{2}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{9}$$

Where; $p= (d/dt)$, R_s, R_r are stator and rotor resistances; L_s, L_r, L_m are stator, rotor and mutual inductances; ψ_{ds}, ψ_{qs} are stator flux in d-q frame; ψ_{dr}, ψ_{qr} are rotor flux in d-q frame; i_{ds}, i_{qs}, i_{qr}, i_{qr} are stator and rotor currents in d-q frame and w_r is rotor speed.

DTC design is very simple and practicable. It consists of three parts such as DTC controller, torque-flux calculator and voltage source inverter (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 [1-6]. The torque produced by the induction motor can be expressed as shown below:

$$T_e = \frac{3}{2}\frac{P}{L_s}\frac{L_m}{L_r}\left|\overline{\psi_r}\right|\left|\overline{\psi_s}\right|\sin\alpha \tag{10}$$

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 (10) 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]:

$$\overline{V}_s = \frac{d\psi_s}{dt} + \overline{i}_s R_s \tag{11}$$

If the stator resistance is ignored, it can be approximated as equation (12) over a short time period [6-7]:

$$\Delta\overline{\psi_s} = \overline{V_s}\Delta t \tag{12}$$

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].

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 block 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 realized.

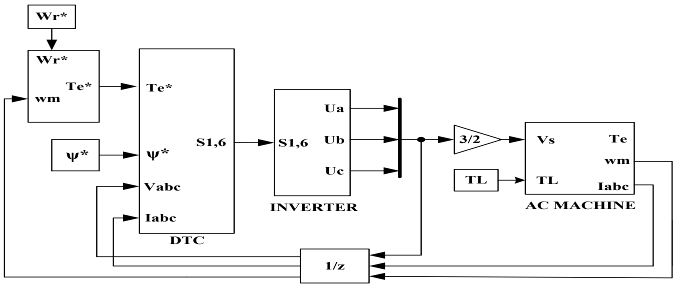

Fig. 1: DTC induction motor system in MATLAB/Simulink environment

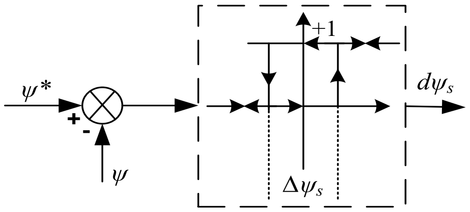

Fig. 2: Two-level flux hysteresis comparator

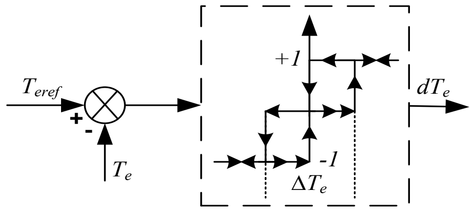

Fig. 3: Three-level torque hysteresis comparator

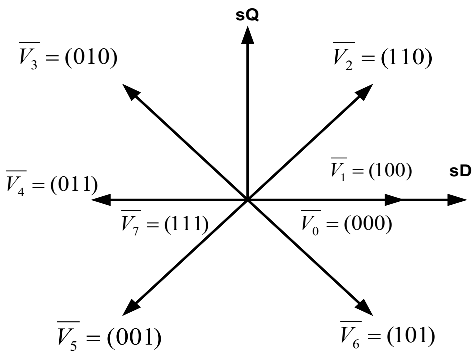

Fig. 4: Voltage vectors

Table 1: Switching Look-up Table

Flux (ψ)	Torque (T_e)	Sectors					
		SS1	SS2	SS3	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. DESIGN OF FLC, PI AND ANTI -WINDUP PI CONTROLLER

In this section, conventional PI controller, PI+AW controller and FLC are designed and applied to the DTC model. In the first design, the conventional PI controller and AW+PI controller are given to apply an induction motor drive in order to control its speed. In the second design, the FLC is designed for stability and robustness control. As a rule, the control algorithm for discrete PI controller can be described as:

$$u_{PI}(k) = K_P e(k) + K_I \sum_{i=1}^{k} e(k) \tag{13}$$

Where, K_P is the proportional factor; K_I is the integral factor and e(k) is the error function. As shown in Fig. 5, the structure of PI controller is really simple and can be implemented easily. An anti-windup integrator is added to stop over-integration for the protection of the system in Fig. 6 [18-21].

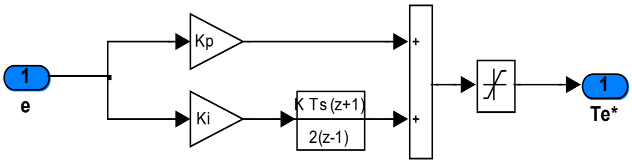

Fig 5: Simulink model of classic PI controller

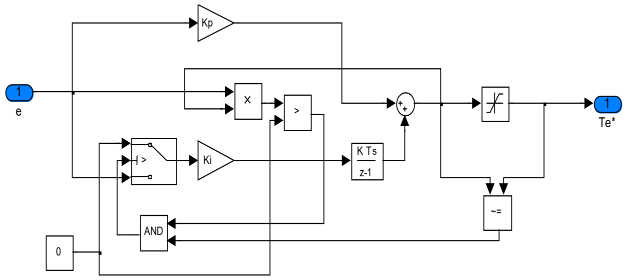

Fig. 6: Simulink model of PI controller with anti-windup

FLC is an appropriate method for designing nonlinear controllers via the use of heuristic information [9, 15]. A FLC system allows changing the control laws in order to deal with parameter variations and disturbances. Especially, the inputs of FLC are speed error and change in the speed error. These inputs are normalized to obtain error e(k) and its change Δe(k) in the range of -1 to +1. The fuzzy membership functions consist of seven fuzzy sets: NB, NM, NS, Z, PS, PM, PB as shown in Fig. 7.

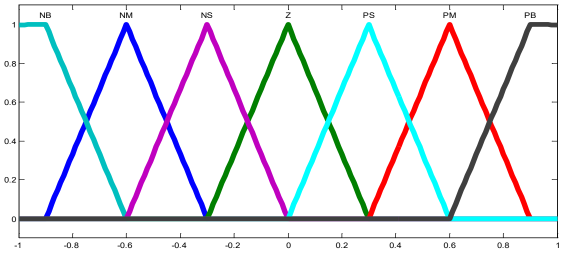

Fig. 7: Membership function of inputs and output

In the FLC, the rule has the form of: IF e is F^k_e AND de is F^k_{de} THEN du is w^k:

$$k = 1,\ldots,M \tag{14}$$

F^k_e and F^k_{de} are the interval fuzzy sets and w^k is singleton output membership functions.

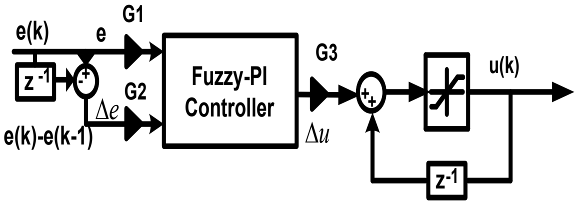

Fig. 8: Block diagram of Fuzzy-PI controller

The rule base of the FLC system is given in Table 2. The block diagram of FLC system for DTC is given in Fig. 8.

Table 2: Rule Base

e de	*NB*	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

4. SIMULATION RESULTS

Several simulation results for speed control of Direct Torque Controlled induction motor drive using PI, PI+AW and FLC is realized in MATLAB/Simulink environment. The simulations are performed for different reference speeds with load of 3N-m and no-load during 2 sec. The parameters of the induction motor used in the simulation are given in Table 3.

Table 3: Induction Motor Parameters

Parameters	Values
Power supply	3Φ
Stator resistance (Rs)	8.231Ω
Rotor resistance (Rr)	4.49Ω
Number of Poles (P)	2
Stator self-inductance (Ls)	0.599H
Rotor self-inductance (Lr)	0.599H
Moment of inertia (J)	0.0019kg-m2
Mutual inductance (Lm)	0.5787H

Fig. 9 shows the performance of PI, PI+AW and FLC. Conventional PI and PI+AW show overshoot during starting (%4.6 and %0.8, respectively). The PI controller response reaches to reference speed after 122 ms with overshoot and PI+AW response reaches to reference speed after 110 ms with overshoot. While the FLC response reaches to steady state after nearly 65 ms without overshoot. The simulation results show the FLC provides good speed response over the PI and PI+AW controller. The FLC performance is better than both of controllers in terms of settling time and maximum peak overshoot. The output torques controlled by PI+AW, PI and FLC controllers is illustrated in Fig. 10, 11 and 12, respectively.

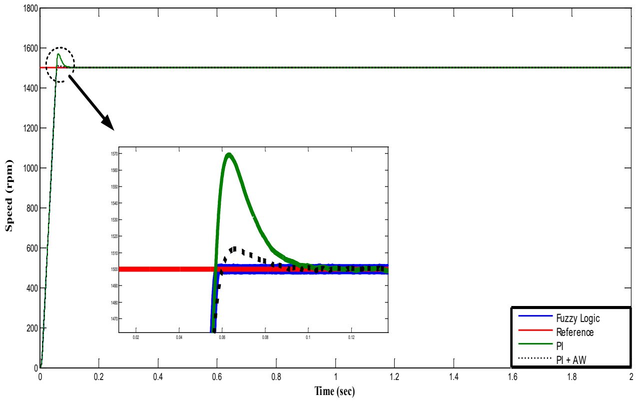

Fig. 9: Speed response comparison at no-load

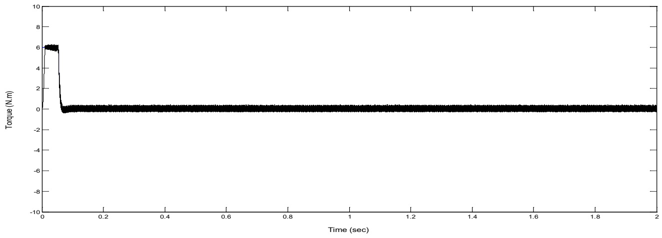

Fig. 10: The output torque response using PI+AW controller

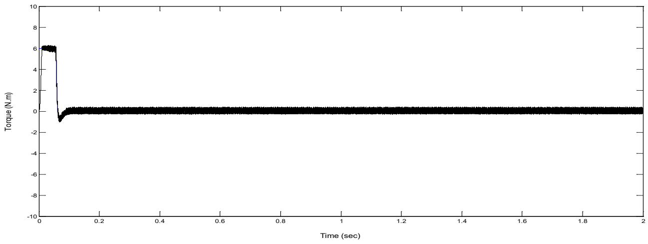

Fig. 11: The output torque response using PI controller

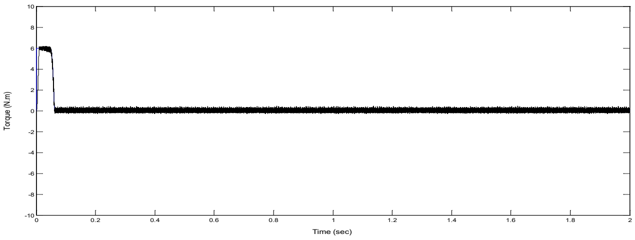

Fig. 12: The output torque response using FLC

Fig. 13 shows the speed tracking performance while sudden changing the speed from 1500 rpm to 1000 rpm at 0.8 sec. Firstly, DTC induction motor starts to operate in a steady state at 1500 rpm reference speed. Then, a sudden step speed command decreasing, from 1500 rpm to 1000 rpm is performed. The simulation results are given in the Fig. 13. The FLC follows the reference speed without any overshoot and steady state error. The performance of the FLC is much better than the PI and PI+AW controller for all speed change cases. The corresponding values are represented in Table 4. The torque responses of PI+AW, PI and FLC are given in Fig. 14, 15 and 16, respectively.

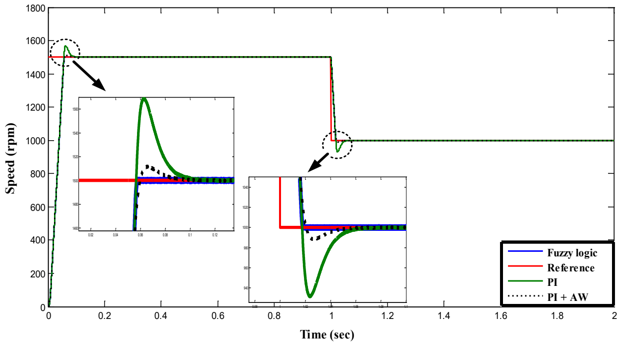

Fig. 13: Speed response comparison at no-load

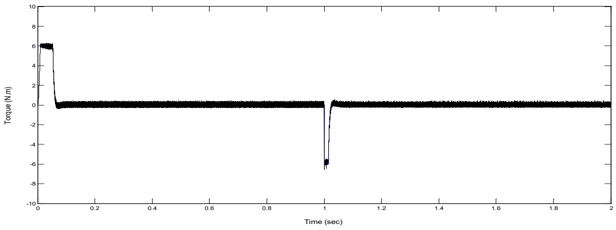

Fig. 14: The output torque response using PI+AW controller

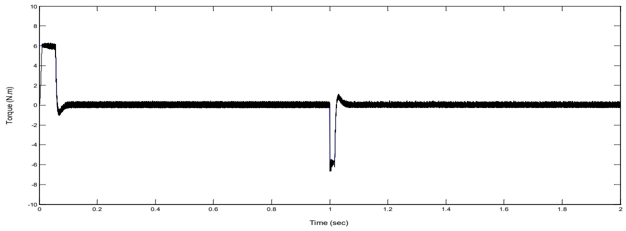

Fig. 15: The output torque response using PI controller

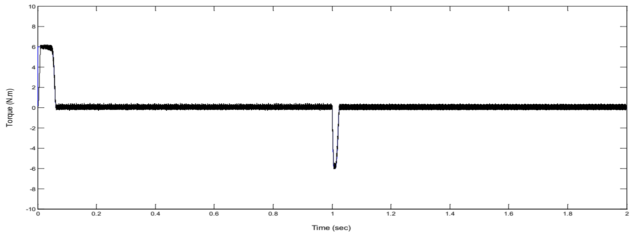

Fig. 16: The output torque response using FLC

Table 4: Performance of Controllers at No-Load

Controller Type	Settling Time ts(ms)	Overshoot Mp (%)
PI Controller	122ms 65ms (response to sudden step reduction)	%4.6(1st peak) %6.8(2nd peak)
PI + AW	110ms 52ms (response to sudden step reduction)	%0.8(1st peak) %1.12(2nd peak)
FLC	58ms 18ms(response to sudden step reduction)	%0(1st peak) %0(2nd peak)

Constant speed responses with load of 3N-m at 0.8sec are given in Fig. 17. The speed response with FLC has no overshoot and settles faster in comparison with PI and PI+AW 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 1500 rpm to 1490 rpm and it takes 3ms to reach the reference speed. The results of simulation show that the FLC gives better responses with respect to settling time and maximum peak overshoot. Moreover, the corresponding values are represented in Table 5. The torque responses of PI+AW, PI and FLC are given in figure 18, 19 and 20, respectively.

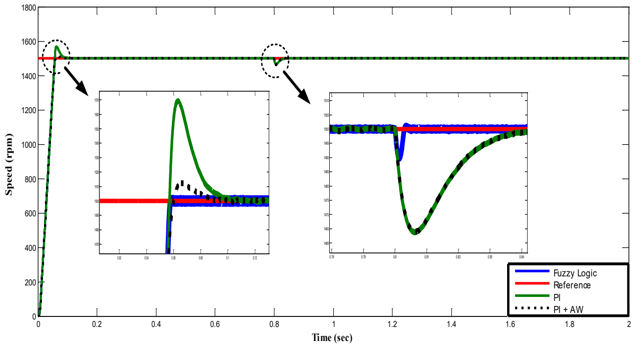

Fig. 17: Constant speed responses with load of 3N-m at 0.8 sec

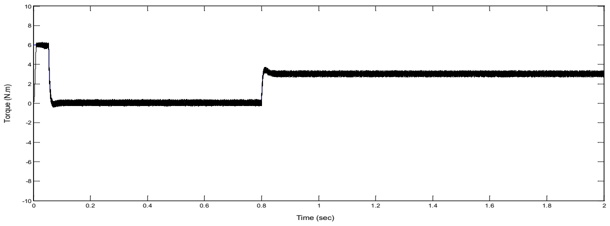

Fig. 18: The output torque response using PI+AW controller

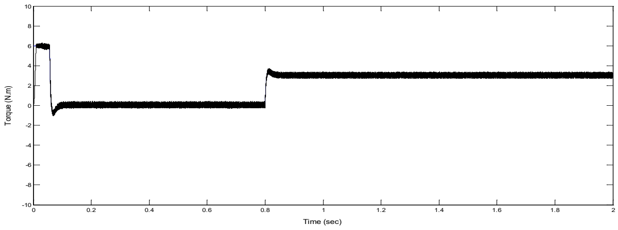

Fig. 19: The output torque response using PI controller

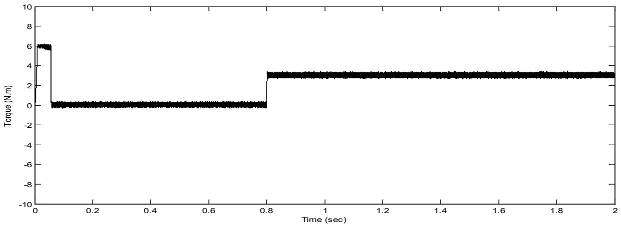

Fig. 20: The output torque response using FLC

Table 5: Performance of Controllers at Load

Controller Type	Settling Time ts(ms)	Overshoot Mp (%)
PI Controller	122ms 42.1ms(response to load torque)	%4.6(1st peak) %2.33(2nd peak)
Anti-Windup PI	110ms 42.1ms(response to load torque)	%0.8(1st peak) %2.33(2nd peak)
FLC	58ms 3ms(response to load torque)	%0(1st peak) %0.66(2nd peak)

5. CONCLUSIONS

In this study, Direct Torque Controlled 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. PI+AW controller, PI and FLC control systems are compared and effectiveness of the FLC against PI and PI+AW control performance is illustrated. Considering the overshoot and the response time, the FLC gives obviously better performance than PI and PI+AW controller. Moreover, it can be seen that the ripple in torque with FLC is less than PI and PI+AW controller for all speed change cases.

References

[1] K. Bose Bimal, “An Adaptive Hysteresis-Band Current Control Technique of a Voltage-Fed PWM Inverter for Machine Drive System,” IEEE Trans. Industrial Electronics, Vol 37, Oct. 1990, pp. 402-408.

[2] I. Takahashi and T. Noguchi, “A new quick-response and high efficiency control strategy of an induction motor,” in IEEE Transactions on Industry Application. Volume. IA, No. 5, 1986, pp. 820-827.

[3] T. G. Habetler, F. Profumo, M. Pastorelli, and L. M. Tolbert, “Direct torque control of induction machines using space vector modulation,” in IEEE Transactions on Industry Applications. Volume: 28, Issue: 5, 1992, pp. 1045 – 1053.

[4] M. Depenhrock. "Direct self-control of inverter-fed machine" IEEE Trans. Power Electron, X988,3:420-429

[5] D. Casadei and G.Serra, “Implementation of direct Torque control Algorithme for Induction Motors Based On Discrete Space Vector Modulation,” IEEE Trans. Power Electronics. Vol.15, No.4, July 2002.

[6] T. G. Habetler, F. Profumo, M. Pastorelli, and L. M. Tolbert, “Direct torque control of induction machines using space vector modulation,” in IEEE Transactions on Industry Applications. Volume: 28, Issue: 5, 1992, pp. 1045 – 1053.

[7] R. Toufouti and H. Benalla, “Direct torque control for induction motor using fuzzy logic,” in ACSE Journal. Volume: 6, Issue: 2, 2006. pp.19-26.

[8] R. Toufouti, and H. Benalla, “Direct torque control for induction motor using intelligent techniques,” in Journal of Theoritical and Applied Information Technology. 2007. pp. 35-44.

[9] F. Sheidaei, M. Sedighizadeh, S.H. Mohseni-Zonoozi, Y. Alinejad- Beromi, “A fuzzy logic direct torque control for induction motor sensorless drive,” in Universities Power Engineering Conference. 2007. pp. 197-202.

[10] Y. Tang and G. Lin, “ Direct Torque control of Induction Motor Based on Self-Adaptive PI Controller,” The 5th

International conference on computer Science & Education, Hefei, China. August 24-27, 2010.

[11] M. Baishan, L. Haihua, Z. Jinping, “Study of Fuzzy control in Direct Torque Control system,” International Conference on Artificial Intelligence and Computational Intelligence, 2009.

[12] N.H. Ab Aziz, A. Ab Rahman, “Simulation on Simulink AC4 model (200HP DTC Induction Motor Drive) Using Fuzzy Logic Controller,” International Conference Computer Applications and Industrial Electronics (ICCAIE) December 5-7, Kuala Lumpu, Malaysia, 2010.

[13] I.Ludthe, "The Direct Control of Induction Motors," Thesis, Department of Electronics and Information Technology, University of Glamorgan, May 1998.

[14] L. A. Zadeh, “fuzzy sets,” Inform, Control, Vol.8, 1965, pp.338-353.

[15] Y.V.Siva Reddy, T.Brahmananda Reddy, M.Vijaya Kumara, “Direct Torque Control of Induction Motor using Robust Fuzzy Variable Structure Controller”, International J. of Recent Trends in Engineering and Technology, Vol.3, No.3, May 2010.

[16] Vinod Kumar, and R.R. Joshi, “Hybrid controller based intelligent speed control of induction motor,” Journal of Theoretical and Applied Information Technology (JATIT), 2005,pp-71-75,

[17] V Chitra, and R. S Prabhakar,. “Induction Motor Speed Control using Fuzzy Logic Controller”, Proc. of World Academy of Science, Engineering and Technology, Vol. 17, December 2006, pp. 248-253.

[18] M. Gaddam, “Improvement in Dynamic Response of Electrical Machines with PID and Fuzzy Logic Based Controllers,” Proceedings of the World Congress on Engineering and Computer Science, WCECS 2007, San Francisco, USA, October 24-26, 2207.

[19] M. Sekkeli, C. Yıldız, H. R. Ozcalik, “Fuzzy Logic Based Intelligent Speed Control of Induction Motor Using Experimental Approach” International Symposium on 1Nnovaitons in intelligent SysTems and Applications, Trabzon/Turkey, June 29, July 1, 2009 INISTA

[20] K.,Klinlaor, C.,Nontawat, “Improved Speed Control Using Anti-windup PI controller For Direct Torque Control Based on Permanent Magnet Synchronous Motor”,12th International Conference on Control, Automation and Systems, Jeju Island/Korea, 17-21 Oct., 2012.

[21] D. Korkmaz, O. G. Koca, Z. H. Akpolat, “Robust Forward Speed Control of a Robotic Fish,” Sixth International Advanced Technologies Symposium, Elazig/Turkey, May 16-18, 2011, pp.33-38.