International Journal of New Technology and Research (IJNTR)
ISSN:2454-4116, Volume-3, Issue-12, December 2017 Pages 42-47

Performance Enhancement of Fuzzy Logic Duty Ratio Controller Based Direct Torque Control of Induction Motor

V.M.Venkateswara Rao, G.Chandra Sekhar, Y.P. Obulesh

***Abstract*--This paper presents reduction of torque ripples in an Induction Motor with DTC by duty cycle controller. The numbers of vectors are increased beyond the available eight discrete voltage vectors are used in this paper without increasing the number of semiconductor switches in the inverter. To achieve swift response, less overshoot and precision speed control to provide to enclose torque speed characteristics, look-up table based online tuning PI controller is projected for outer speed control loop. This paper shows a new algorithm for optimized value of stator flux based on the maxim reference value of electromagnetic torque to operate in conjunction with duty ratio control. MATLAB-Simulink is used to observe the performance of proposed technique. The simulation results shows the improved results of the proposed technique compared over the existing methods.**

***Index Terms*-- direct torque control, fuzzy logic duty ratio controller, induction motor.**

I. INTRODUCTION

Over the years direct torque control (DTC) of induction motor emerged as an alternative to field oriented control of induction motor [1]. DTC is employed for high performance and quick response drives [2].Compared to field oriented control, DTC has following advantages like (a) simple and quick response control, (b) absence of co-ordinate transformation and current controllers, (c) PI controllers in Flux and torque control loops[3-4]. The conventional DTC (CDTC) suffers from major disadvantages like (a) high torque and flux ripples, (b) accurate estimation of torque and flux, (c) sluggish speed response during low speed and sudden change in torque command and (d) variable switching frequency [3-5]. Over the last two decades several solutions are proposed by researches to improve CDTC. Few researches proposed improvements in CDTC by employing multilevel inverters [6-8], but multi level inverters results in high switching losses. Few developed DTC with variable gain hysteresis bands or by replacing hysteresis band with constant switching controllers [9-10]. CDTC is also improved by space vector modulation and discrete space vector modulation techniques as given in [11-13] but in these methods accurate design of torque and flux loop PI controllers is required. The use of artificial intelligent techniques like neural networks, fuzzy logic for improvements in CDTC gained more importance in recent years. In order to improve CDTC few researchers did works on replacing conventional torque and speed PI controllers with fuzzy, neuro-fuzzy (ANFIS), sliding mode fuzzy and neural network controllers [13-16]. It results in improved transient response but there is nothing much reduction in torque and flux ripples under steady state. Improvements in steady state performance of CDTC using ANN based switching controller is proposed in [17-18]. Improvements in CDTC using fuzzy logic switching controller is proposed by [3, 19-22] and using hybrid AI technique is given by [23-24]. Implementation of ANN requires training of neural network for set of inputs and outputs based on black box approach. The performance of ANN depends upon selected structure of ANN number of iterations. The drawback on ANN based switching controller is, it does not give heuristic knowledge of process in selection of optimal switching vector. We can overcome the drawback of ANN using hybrid neuro-fuzzy switching controller. In neuro-fuzzy the architecture of system is known and system behavior is decided by fuzzy rule base generated based on ANN. Neuro fuzzy useful for systems whose domain knowledge is not known or expert cannot formulate the rule base. The selection of optimal switching state in DTC is well defined and shifting of one switching state to another depends upon torque error, flux error and stator flux space sector. Fuzzy logic is knowledge based system gives heuristic reasoning of the process. Fuzzy logic is an excellent tool to handle uncertainty in nonlinear function. Fuzzy logic process is easy to understand due to its simple logical structure and inference mechanism.

The work presented in this paper considers the design of new fuzzy logic controller with five membership functions for the inputs and output along with the optimized flux algorithm based on maximum reference value of the electromagnetic torque to adjust the “duty ratio” of inverter switching vectors. The present work shows much better performance (reduced ripple) though it has some similarities with those in [25-27]. A significant reduction in the ripple than that in [28-29] has been achieved in the present work. The adaptive PI controller that is based on look-up Table is used for outer speed loop for precision speed tracking. A series of simulation tests are conducted using MATLAB-SIMULINK package to validate the performance of the devised algorithm.

The complete paper is organized as follows: Section 2 explains strategy of torque ripple minimization. Section 3 discusses design of fuzzy logic duty ratio controller. The simulation results, comparison and discussion are presented in Section 4. Section 5 concludes the work.

II. TORQUE RIPPLE MINIMIZATION STRATEGY

Despite of the available complex solutions [26-36] the duty ratio scheme presents best remedy to minimal torque and

V.M.Venkateswara Rao, Research Scholar, Department of Electrical and Electronics Engineering, K L University, Andhra Pradesh, India.
G.Chandra Sekhar, Professor, Department of Electrical and Electronics Engineering, K L University, Andhra Pradesh, India.
Y.P.Obulesh, Professor, Department of Electrical and Electronics Engineering, K L University, Andhra Pradesh, India.

flux ripple, by overshadowing the above-mentioned existing methods. In the classical DTC, a voltage vector is applied for the entire switching period, and this causes the stator current and electromagnetic torque to increase over the whole switching period. Thus for small errors, the electromagnetic torque exceeds its reference value early during the switching period, and continues to increase, causing a high torque ripple. This is then followed by switching cycles, where the null switching vectors are applied to set the electromagnetic torque to its reference value.

The ripple in the torque and flux can be easily reduced by applying the selected inverter vector only for the part and not for the entire switching period unlike that in the classical DTC IM drive. The time for which an active voltage vector has to be applied is chosen just to increase the electromagnetic torque to its reference value and the null voltage vectors are applied for the rest of the switching period. During the application of the null vectors the motor absorbs no power, and thus the electromagnetic torque is almost constant or decreases slightly. But this decrease should be small to have minimum torque ripple. Since this decrease in torque also depends on the modulus of the reference stator flux, an optimized value for the flux has to be used, which is large enough to generate the reference torque. This implies that the maximum electromagnetic torque reference has to be found and the optimized stator flux reference corresponds to this, as follows: The expression of stator current space vector in stator flux oriented reference frame can be obtained as,

$$\bar{\mathrm{i}}_{\mathrm{s}} = \frac{\left(\frac{\mathrm{L_m}}{\mathrm{L_s}}\right)\left|\bar{\psi}_{\mathrm{s}}\right|(\mathrm{R_r}+\mathrm{i}\omega_{\mathrm{sl}}\,\mathrm{L_r})}{(\mathrm{R_r}+\mathrm{j}\mathrm{w}\,\omega_{\mathrm{sl}}\,\sigma\mathrm{L_r})} \qquad (1)$$

The imaginary part of the above equation gives the torque producing stator current ($\mathrm{i_{sy}}$) and maximum value of this occurs at $\omega_{\mathrm{sl,\ max}} = 1/\mathrm{T'_r}$ ($\mathrm{T'_r}$ denotes the rotor transient time constant). By substituting the corresponding $\mathrm{i_{sy,\ max}}$ value in the electromagnetic torque expression, $\mathrm{T_e} = 3/2(\mathrm{P}/2)|\bar{\psi}_s \times \bar{\iota}_s$ of induction motor, the maximum torque can be evaluated as follows:

$$\mathrm{T_{e,\ max}} = 3/2(\mathrm{P}/2)|\bar{\psi}_s \times \bar{\iota}_{sy,max} \qquad (2)$$

The maximum electromagnetic reference torque can be found from the above equation by substituting, $\mathrm{T_e}$ shown in equation (3).

$$T_{e,ref}^{max} = \frac{3}{4}\,\frac{P}{2}\left(\frac{L_M}{L_S}\right)^2 \frac{|\bar{\psi}|^2}{\sigma L_r} \qquad (3)$$

The optimized reference flux linkage for the given maximum electromagnetic torque reference can be calculated by setting, $\left|\bar{\psi}_{\mathrm{s,ref}}\right| = \left|\bar{\psi}_{\mathrm{s}}\right|$ as in equation (4).

$$\left|\bar{\psi}_{s,ref}\right| = \sqrt{\frac{8T_{e,ref}^{max}\,L_S^2\sigma L_r}{3PL_m^2}} \qquad (4)$$

When the above optimized stator flux linkage value is used in DTC induction motor drive along with duty ratio control, the torque ripples reduce significantly. But, the duty ratio of each switching period is a non-linear function of the electromagnetic torque error($\mathrm{E_{Te}}$) stator flux-linkage error ($\mathrm{E}_{\psi\mathrm{s}}$) and the position of the stator flux-linkage space vector (ρ_{s}). It is difficult to model such non-linear function. However, the characteristics (such as, model free nature and non-dependence on mathematical equations [17]) of fuzzy logic controller make the duty ratio determination possible and easier during every switching period.

III. PROPOSED METHODOLOGY

Figure-1 shows the schematic of proposed DTC IM drive with fuzzy logic based duty ratio control. Two Mamdani type fuzzy logic controllers (FLC-1 and FLC-2) that contain fuzzifier, inference engine, rule base, and defuzzifier are chosen. The FLC-1 and 2 are used for positive and negative flux error respectively. In classical DTC, outer loop speed regulators are conventional PI controllers, which require precise math model of the system and appropriate value of PI constants to achieve high performance drive. Therefore, unexpected change in load conditions or environmental factors would produce overshoot, oscillation of the motor speed, oscillation of the torque, long settling time and, thus causes deterioration of drive performance. To overcome this problem, a look-up Table is designed from the experiences of speed response of classical DTC. According to the speed error and change of speed error, the proportional and integral gains are adjusted on-line.

A. Selection of input/output variables

The design starts with assigning mapped input/output variables of FLC. In this work, the first input variable is the torque error ($\mathrm{E_{Te}} = \mathrm{T_{e,ref}} - \mathrm{T_e}$) and the second input variable is the stator flux vector position (ρ_{s}) at a sampling time t_s. The output variable is duty ratio (δ).

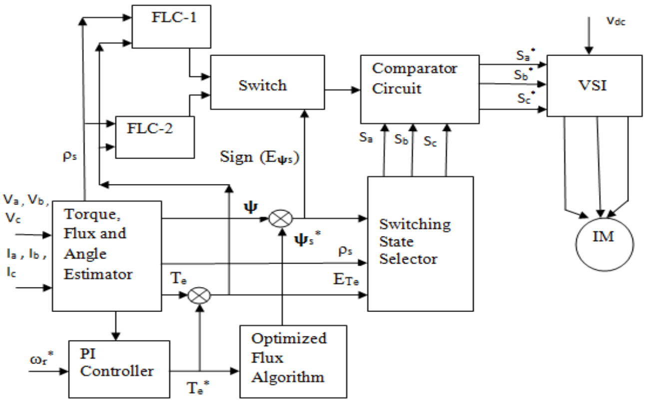

Figure-1: Schematic diagram of proposed DTC with fuzzy logic duty ratio controller

B. Fuzzification

The success of robust fuzzy controller design mainly depends upon this stage. In this stage the crisp variables of the inputs $\mathrm{E_{Te}}(\mathrm{t_s})$ and $\rho_{\mathrm{s}}(\mathrm{t_s})$ converted into fuzzy variables $\mathrm{E_{Te}}$ and ρ_{s} that can be identified by the levels of membership in the fuzzy set. Each fuzzy variable is a member of the subsets with a degree of membership μ varying between 0 (non-member) and 1 (full member).

To make the torque and duty ratio variations smaller, the universe of discourse of torque error and duty ratio are divided into five overlapping fuzzy sets. However, to reduce the complexity of design, the stator flux position is defined with three overlapping fuzzy sets only. The universe of discourse of all the variables, covering the whole region is expressed in per unit values. The fuzzy subsets are defined with triangular membership functions as shown in Figure-2. The linguistic labels are defined as VS = Very Small, S = Small, M = Medium and L = Large, VL = Very Large.

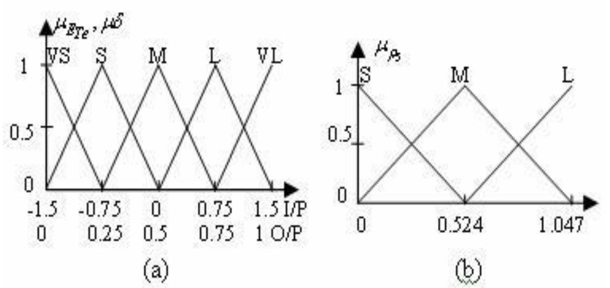

Figure-2. Membership functions for (a) torque error and duty ratio (b) stator flux position

C. Rule base and fuzzy inference engine

The Rule base involves defining the rules in IF-THEN form, which govern the relation between input and output variables in terms of membership functions. In this stage the input variables are processed by the inference engine that executes 15 rules (5x3) as shown in Table-1. These rules are generated from the knowledge of control systems and the simulation results of classical DTC induction motor using different switching states. The inference engine also includes the application of fuzzy operator (AND, OR), product operation of fuzzy implication and maximum aggregation. The relation between different conditions in the same rule is done by means of 'AND' operator. On the other hand, the relationship between different rules is done by means of 'OR' operator.

Table-1. Fuzzy control rules for duty ratio determination.

$E_{\psi e}$	ρ_s \ E_{Te}	VS	S	M	L	ML
$\lvert\overline{\psi}_s\rvert < \lvert\overline{\psi}_{s,ref}\rvert$	S	S	M	M	L	VL
	M	VS	S	M	L	VL
	L	VS	S	M	L	VL
$\lvert\overline{\psi}_s\rvert > \lvert\overline{\psi}_{s,ref}\rvert$	S	VS	S	M	M	VL
	M	VS	S	M	L	VL
	L	S	M	L	VL	VL

D. Defuzzification

This stage introduces different inference methods that can be used to produce the fuzzy set values for the output fuzzy variables. In this paper, the center of gravity (COA) or centroid method is used to calculate the final fuzzy value. The COA expression with a discretized universe of discourse can be written as,

$$\delta = \frac{\sum_{i=1}^{n} \delta_i \mu_{out}(\delta_i)}{\sum_{i=1}^{n} \mu_{out}(\delta_i)} \quad (5)$$

Where, *n* denotes the total number of rules. The comparator circuit as shown in Figure-1, compares the duty ratio determined during each switching period with a triangular signal, whose period is equal to that of switching period and thus determines the duration for which active vector should be applied. The modified symmetrical switching vectors fed to the inverter would improve the performance of drive.

IV. RESULTS COMPARISON AND DISCUSSIONS

A series of simulation tests are conducted on a 4KW, 4pole inverter-fed IM to evaluate the performance of proposed DTC method.

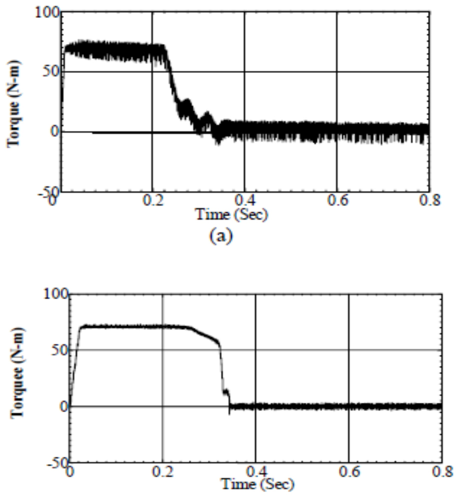

Figure-3. Simulation results for torque response with reference speed of 157 rad/sec and no load (a) classical (b) proposed DTC.

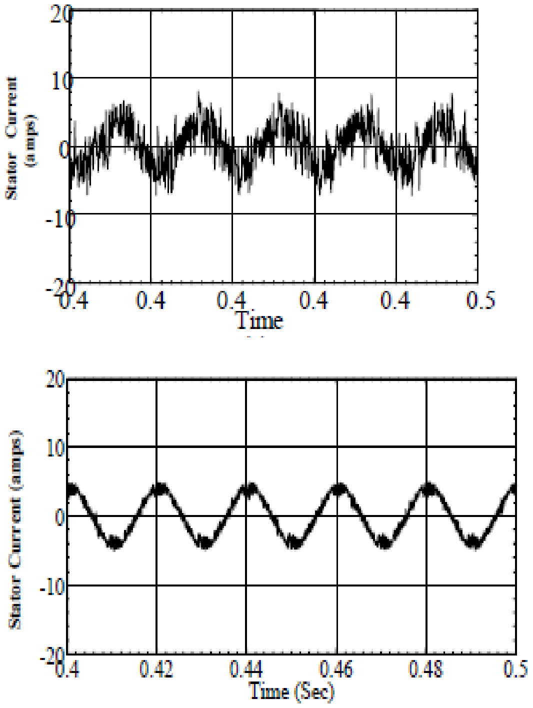

Figure-4: Simulation results for stator current with reference speed of 157 rad/sec and no load (a) classical DTC (b) Proposed DTC

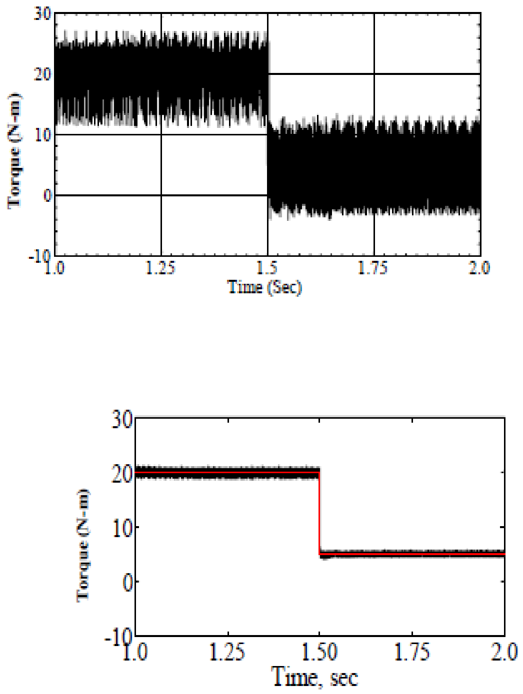

Figure-5. Simulation results for electric torque response (a) Classical DTC with reference speed of 157 rad/sec and step load (b) proposed DTC with reference speed of 157 rad/sec and step load.

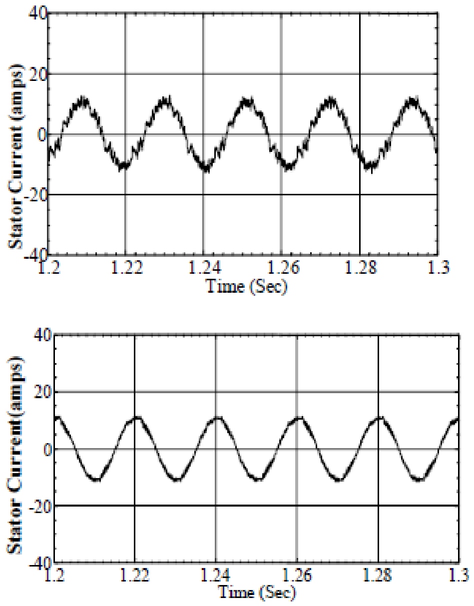

Figure-6. Simulation results for stator current with reference speed of 157 rad/sec and step load (a) classical DTC (b) proposed DTC

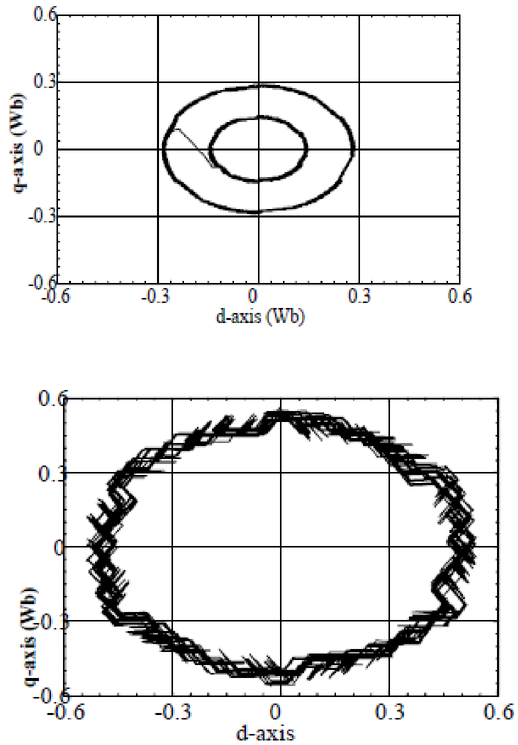

Figure-7. Simulation results for stator flux trajectory with reference speed of 157 rad/sec and step load (a) classical DTC (b) proposed DTC

The torque response has been analyzed in steady state. These tests are carried out for 157-rad/sec speed operation, with sudden drop in load torque from 20N-m to 5N-m at 1.5sec. A constant un-optimized stator flux value of 0.5 Wb is used for classical DTC. Whereas, optimized stator flux values of 0.3734Wb (for 20N-m load) and 0.1867 Wb (for 5N-m load) are used for proposed one.

Figure-3(a) and 3(b) shows electric torque response for classical DTC and proposed DTC respectively for no load operation. In addition to the inherent disadvantage of classical DTC, the constant reference flux causes higher ripple at lower torque level because, the chosen 0.5 Wb is larger than the optimized flux value (0.1867Wbs). But, the proposed method causes lower ripple at lower torque level than at the higher torque level. Moreover, this method is able to eliminate the torque undershoot and overshoots. The average amount of ripple reduction in torque compared to classical DTC is observed to be $1/19^{th}$ (~11N-m for classical with peaks up to ~16N-m, and ~1.2N-m for proposed) and $1/15^{th}$ (~15N- for classical with peaks up to ~19N-m, and ~1N-m for proposed) respectively for higher and lower torque levels of high-speed operation. Similarly, for low speed operation the reduction is observed to be more than $1/10^{th}$ (~9N-m for classical with peaks up to ~14N-m, and ~0.8N-m for proposed) and $1/17^{th}$ (~11N-m for classical with peaks up to ~15N-m, and ~0.6N- m for proposed) respectively for higher and lower torque levels. Figure-4(a) and 4(b) shows no-load stator currents for classical and proposed DTC respectively for a reference speed of 157 rad/sec. Figure-5(a) and 5(b) shows electric torque response for classical DTC and proposed DTC respectively for a step load, Figure-6(a) and 6(b) shows stator currents for classical and proposed DTC respectively for a reference speed of 157 rad/sec for a step load and Figure-7(a) and 7(b) shows stator flux trajectory for classical and proposed DTC respectively for a reference speed of 157rad/sec and with a step load.

V. CONCLUSIONS

In this study, on- line PI tuning and torque ripple minimization strategy are brought to a common platform to alleviate the disadvantages of classical DTC employed to control an inverter-fed induction motor drive. The fuzzy logic duty ratio controller with optimized reference flux command is applied and verified. Low speed operation of the proposed method dictates the proper functionality of speed estimation as well as precision torque control. From the simulation tests the following justifiable conclusions are drawn against the existing solutions.

The devised method is easier to understand, design and implement. The input/output scaling factors for fuzzy logic controller are absent;

a) Increased efficiency as well as lower acoustic noise for the induction motor drive is observed because of the significant reduction (~1/15th) in torque, flux and current ripples/harmonics. In addition to the torque ripple minimization, under (over) shoots are also eliminated;
b) The proposed method operates at a lower switching frequency, and thus reduces switching losses as well as stress on semiconductor switches of the inverter;
c) From the simulation results shown, it is clear that, the proposed method of DTC will reduce the torque and flux ripple considerably; and
d) The smoother flux trajectory for the proposed method of DTC confirms the ripple reduction in torque, flux, stator current and speed response.

3-Phase Induction Motor Parameters: Rotor type: Squirrel cage

Symbol	**Parameter**	**Values**
n	Motor Speed	1440rpm
f	Supply Frequency	50Hz
P_n	Power	4kw
P	Pole pair	4
R_s	Stator Resistance	1.57Ω
R_r	Rotor Resistance	1.21 Ω
Ls	Stator Inductance	0.17 H
L_r	Rotor Inductance	0.17 H
L_m	Mutual Inductance	0.165 H
J	Moment of Inertia	0.06 Kg-m^2

REFERENCES

[1] Takahashi I, Naguchi T. A new quick-response and high efficiency control strategy of an induction motor. IEEE Transactions on Industry Applications.1986; Vol. 22(5), pp. 820-827.
[2] Takahashi I, Y. Ohmori. High-Performance Direct Torque Control of an Induction Motor. IEEE Trans. On Industry Applications. 1989; vol. 25(2), pp.257-264.
[3] Milan Zalman, IvicaKuric. Direct Torque and flux control of Inductionmotor and fuzzy controller. Journal of Electricalengineering. 2005; Vol. 56(9-10), pp.278–280.
[4] Sudheer H, Kodad SF, Sarvesh B. Torque Ripple Reduction in Direct Torque Control of Induction Motor using Fuzzy Logic based duty Ratio Controller. International Journal of Electronic Engineering Research. 2011; Vol 3(1), pp.1-12.
[5] Kazmierkowski, M.P. Kasprowicz A.B., Improved direct torque and flux vector control of PWM inverter-fed inductionmotor drives. IEEE Transactions on Industrial Electronics.1995; vol.42(4), pp.344-350.
[6] Kyo-Beum Lee, Joong-Ho Song, Choy I, Ji-Yoon Yoo. Torque ripple reduction in DTC of induction motor driven by three-level inverter with low switching frequency., IEEE Transactions on Power Electronics.2002; vol.17(2), pp.255- 264.
[7] M. F. Escalante, J. C. Vannier and A. Arzande. Flying capacitor multilevel inverters and DTC motor drive applications. IEEE Transactions on Industrial Electronics.2002; vol. 49(4), pp. 809-815.
[8] F. Khoucha, S. M. Lagoun, K. Marouani, A. Kheloui and M. E. H. Benbouzid. Hybrid Cascaded H-Bridge Multilevel- Inverter Induction-Motor-Drive Direct Torque Control for Automotive Applications. IEEE Transactions on Industrial Electronics, 2010; vol. 57(3) pp. 892-899.
[9] Jun-Koo Kang, Dae-Woong Chung and Seung-Ki Sul, Direct torque control of induction motor with variable amplitude control of flux and torque hysteresis bands.International Conference on Electric Motors and Drives.1999:640-642.
[10] N. R. N. Idris and A. H. M. Yatim. Direct torque control of induction motors with constant switching frequency and reduced torque ripple. IEEE Transactions on Industrial Electronics. 2004, vol. 51(4), pp. 758-767.
[11] G. Habetler, F. Profumo, M. Pastorclli, L.M. Tolbert, "Direct Torque Control of Induction Motors Using Space Vector Modulation.", IEEE Transactions on Industry Applications, 28(5): 1045-1053, September/October, 1992.
[12] D. Casadei, G. Sera, ATani. Implementation of a Direct Torque Control Algorithm for Induction Motors Based on Discrete Space Vector Modulation. IEEE Transactions on Power Electronics,2000; Vol. 15(4) pp.769-777.
[13] F. Barrero, A. Gonzalez, A. Torralba, E. Galvan and L. G. Franquelo. Speed control of induction motors using a novel fuzzy sliding-mode structure. IEEE Transactions on Fuzzy Systems, 2002; vol. 10(3), pp. 375-383.
[14] SM Gadoue, D Giaouris, J.W. Finch. Artificial intelligence based speed control of DTC induction motor drive- A comparative study. Journal of Electronics power research, 2009; pp.210-219.
[15] Yen-Shin Lai, Juo-Chiun Lin. New hybrid fuzzy controller for direct torque control induction motor drives, IEEE Transactions on Power Electronics, 2003; vol. 18(5) pp1211-1219.
[16] [Sudheer H, Kodad SF and Sarvesh B, Fuzzy Direct Torque and Flux Control of Induction Motor Using Fuzzy Speed controller, i-Manager's Journal on Electrical Engineering, 2013; Vol. 6 pp.14-21.
[17] Xuezhi Wu, Lipei Huang. Direct torque control of three-level inverter using neural networks as switching vector selector. In:IEEE Conference Record of the Industry Applications 2001, (2):939-944. doi: 10.1109/IAS.2001.955565
[18] S. Gdaim, A. Mtibaa, M. F. Mimouni. Direct Torque Control of Induction Motor based on Intelligent Techniques. International Journal of Computer Applications 2010; 10(8):29-34.
[19] S. A. Mir, M. E. Elbuluk, D. S. Zinger. Fuzzy implementation of direct self-control of induction motors. IEEE Transactions on Industry Applications 1994; 30(3):729-735.doi: 10.1109/28.293723.
[20] S. Gdaim, A. Mtibaa and M. F. Mimouni. Design and Experimental Implementation of DTC of an Induction Motor Based on Fuzzy Logic Control on FPGA. IEEE Transactions on Fuzzy Systems, 2015; vol. 23(3), pp. 644-655.
[21] R. Toufouti, S. Meziane, H. Benalla. Direct torque control for induction motor using fuzzy logic, ACSE Journal, 2006; vol. 6(2) pp.19–26.
[22] H. Sudheer, S. Kodad and B. Sarvesh, Direct Torque and Flux control of induction motor using Fuzzy Logic controller, 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Chennai, 2016; pp. 193-197. doi: 10.1109/AEEICB.2016.7538271.
[23] P. Z. Grabowski, M. P. Kazmierkowski, B. K. Bose, F. Blaabjerg. A simple direct-torque neuro-fuzzy control of PWM-inverter-fed induction motor drive. IEEE Transactions on Industrial Electronics2000; 47(4):863-870. doi: 10.1109/41.857966
[24] Fayez G. Areed, Amira Y. Haikal, Reham H. Mohammed. Adaptive neuro-fuzzy control of an induction motor. Ain Shams Eng J 2010; 1(1): 71-78.http://dx.doi.org/10.1016/j.asej.2010.09.008.

[25] Bird I. G and H. Zelaya De La Parra. 1997. Fuzzy logic torque ripple reduction for DTC based AC drives. Electronics Letters. 33(17): 1501-1502.

[26] Habetler G H, Francesco Profume, Michele Pastorelli and Leon M Tolbert. 1992. Direct Torque Control of Induction Machines using Space Vector Modulation. IEEE Trans. Industry Applications. 28(5): 1045-1053.

[27] Peter Vas. 1998. Sensorless Vector and Direct Torque Control. New York: Oxford University Press

[28] Malik E. Elbuluk. 2003. Torque Ripple Minimization in Direct Torque Control of Induction Machines. IEEE-IAS annual meeting. 1: 12-16

[29] Sayeed Mir and Malik E.Elbuluk. 1995. Precision Torque Control in Inverter- Fed Induction Machines using Fuzzy Logic. IEEE-IAS annual meeting.pp.396-401

[30] Habetler G. Thomas and Deepakraj M. Divan. 1991. Control Strategies for Direct Torque Control using Discrete Pulse Width Modulation. IEEE Trans. Industry Applications. 27(5): 893-901.

[31] Isao Takahashi and Ohmori Youichi. 1989. High-Performance Direct Torque Control of an Induction Motor. IEEE Trans. Industry Applications. 25(2): 57-264.

[32] Kang J. K., Sul. S. K. 1998. Torque Ripple Minimization Strategy for Direct Torque Control of Induction Motor. IEEE-IAS annual meeting. pp. 438-443.

[33] Lascu C., Boldea. I, Blaabjerg. 1998. A Modified Direct Torque Control (DTC) for Induction Motor Sensorless Drive. IEEE-IAS Annual Meeting. pp. 415-422.

[34] Li Y, Shao Jianwen and Si Baojun. 1997. Direct Torque Control of Induction Motor for Low Speed Drives Considering Discrete Effects of Control and Dead-time of Inverters. Proc. Of Conf. Rec. IEEE-IAS Annual. Meeting. 97: 781-788

[35] Senthil Udayar and Fernandes B.G.2003. Hybrid Space Vector Control of Induction Motors without Rotational Transducers. IEEE Trans. Industry Applications.28(5):1054-1061.

[36] Walczyna A. M. and Hill R. J. 1993. Space Vector PWM Strategy for 3-Level Inverter with Direct Self-Control. Proc. of 5th European Conference on Power Electronics and Applications. 4(377): 152-157.

[37] Lee. C. C. 1990. Fuzzy Logic in Control Systems: Fuzzy Logic Control - Part 1. IEEE Transactions on Systems, Man and Cybernetics. 20(2): 404-418.