An Experimental Examination of a Fuzzy Logic-Based DTC Scheme

H. Valizadeh Haghi, B. Eskandari, E. Pashajavid, M. Tavakoli Bina
Dept. of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran
E-mails: valizadeh@ieee.org, eskandari@ieee.org, pashajavid@ieee.org, tavakoli@eetd.kntu.ac.ir

Abstract— **Direct torque control (DTC) of an induction motor is a relatively simple scheme making rapid computations while requiring no speed sensors. It indicates low sensitivity to parameter variations as well. Accordingly, it has become a promising alternative to the classic vector control methods. This paper reports an experimental implementation of a DTC scheme. As one of the main characteristics of the conventional DTC is the torque ripple, the most of our efforts have been placed to reduce this ripple in practice. A fuzzy logic-based approach has been employed to achieve a better drive performance by varying the duty ratio of the selected voltage vector during each switching period according to the magnitude of the torque error and position of the stator flux. The main objective throughout the reported research project is to achieve an operational setup but not to propose a new theory. The effectiveness of the control method was verified by simulation using Simulink, and experimentally using TMS320F2812 DSP-controlled setup.**

Keywords- Digital signal processor; direct torque control; pulse-width modulation.

I. INTRODUCTION

Following the outstanding advances in semiconductor technology and power electronics during the last 20 years, the movement toward developing an ideal induction motor drive has been considerable. However, the improvements either as the efficiently performing switches or as the possibility of implementing complex algorithms in the new microprocessors need to be complemented by some efficient control methods. Indeed, considering non-linear and multivariable characteristics of a real motor-drive system makes the development of an ideal control method a profound research work.

A considerable research effort has been devoted to this field with the aim of finding simpler methods of speed/torque control for induction machines. As a result, field-oriented control (FOC) and direct torque control (DTC) are becoming the industrial standards for induction motors torque control [1]. These two methods indicate comparable performance by and large; however, the DTC is simpler to be implemented. The less computational time of implementing a DTC as a sensorless control technique with a good performance in steady-state and transient operating conditions, makes this technique a viable choice for industrial uses.

On the other hand, there have been proposed various types of techniques to solve some of the problems, inherently associated with the DTC [1]; among them is using fuzzy techniques to moderate the torque ripple as one of the main disadvantages (e.g. [2-7]). The torque and flux ripples in the classical DTC induction motor drive are due to the fact that none of the inverter switching vectors is able to produce the desired changes in both torque and stator flux. Various techniques has been proposed to reduce these ripples; for example, setting up a higher switching frequency or a change in the inverter topology [8]. However, the duty ratio control by fuzzy rules [4-5, 7] seems to be a good alternative as it would not deteriorate the computational efficiency very much while it keeps the switching losses at an acceptable level. As shown [5, 7], fuzzy logic approach controls the duty ratio of switching states such that the torque ripple can be significantly reduced. It should be noted that using a higher switching frequency requires a fast processor and increases the cost as well.

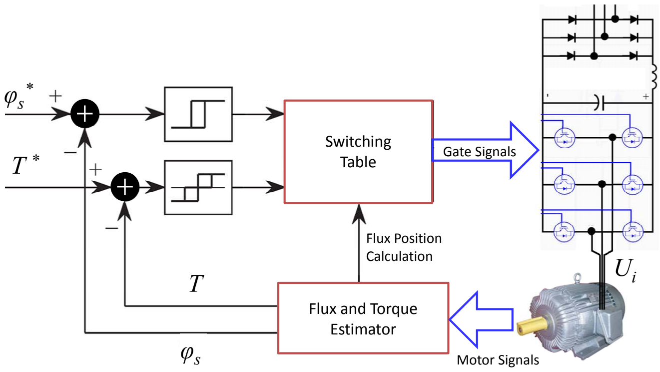


Figure 1. Basic DTC scheme.

On the basis of the experience of the authors, all improvements to the basic DTC contributed to a better performance, nevertheless, they could deteriorate the computational efficiency as a main advantage. Therefore, according to the specific features of the related research project, using a fuzzy control plan has been preferred in this paper. An improved DTC scheme based on the fuzzy duty ratio approach has been examined experimentally. The basic theoretical idea is taken from [4] with some improvements and practical considerations. Furthermore, an optimized flux reference is employed. Much emphasis is being placed on setting up an experimental DTC drive having a minimum torque ripple at high speed while preserving an acceptable computational efficiency. So, the methods and strategies have been selected and optimized to achieve this goal in practice.

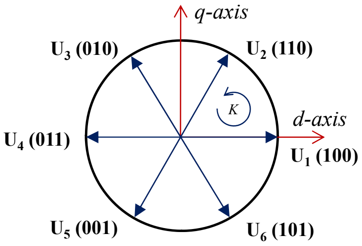


Figure 2. The voltage vectors of a two-level three-phase VSI of Fig. 1.

TABLE I. Different Choices for Basic Switching Table of DTC

	T_e↑ $\lvert\varphi_s\rvert$↑	T_e↑ $\lvert\varphi_s\rvert$↓	T_e↓ $\lvert\varphi_s\rvert$↑	T_e↓ $\lvert\varphi_s\rvert$↓
Scheme 1	U_{K+1}	U_{K+2}	U_0, U_7	U_0, U_7
Scheme 2	U_{K+1}	U_{K+2}	U_K	U_0, U_7
Scheme 3	U_{K+1}	U_{K+2}	U_K	U_{K+3}
Scheme 4	U_{K+1}	U_{K+2}	U_{K-1}	U_{K-2}

II. Basic Idea of DTC

The basic DTC idea is shown in Fig. 1 schematically. A three level hysteresis comparator is used for making a decision signal based on the error between the estimated value and the reference value of the electromagnetic torque and a two level comparator is used for the flux error in the same way. Reference quantities are depicted by a star superscript. The basic idea of the DTC, as the “switching table” block in Fig. 1 is in control of it, is to choose the best voltage vector, which relocates the flux vector to produce the desired torque. The tip of the flux vector should be maintained inside a predefined band in the relocating process.

The resulting gate signals correspond to a set of six nonzero voltage vectors and two zero voltage vectors producible from a three-phase voltage source inverter (VSI), as shown in Fig. 2. The real-time torque in Fig. 1 can be estimated by

$$T = \frac{3}{2} p \bar{i}_s \cdot j\bar{\varphi}_s \, , \tag{1}$$

whereas the stator flux is calculated by a flux observer or in relation to the measured voltage and current vectors suitable for high speed range [9],

$$\bar{\varphi}_s = \int \left(\bar{u}_s - R_s \bar{i}_s \right) dt. \tag{2}$$

The rotation of the stator flux vector could be considered in six symmetrical sectors corresponding to the voltage vectors shown in Fig. 2. A suitable voltage vector is applied to the motor to keep up the flux and torque with their reference value. The basic switching methods that have been proposed for this purpose are shown in Table I [10]. The parameter K represents the number of the stator flux sectors. As can be seen, applying the vectors U_{K+1} and U_{K+2} increases the torque while applying the vectors U_{K-1} and U_{K-2} decreases the torque within the current step. The first scheme is preferred in this research.

III. Improved-DTC to Minimize Torque Ripples

As it is mentioned in the introduction, our purpose is to set up an experimental DTC with an emphasis on achieving a small torque ripple to be trade off against computational efficiency. In this regard, two well-established methods, optimal flux selection and fuzzy duty ratio control, are studied in the following sections and employed in parallel with each other for the experimental examination setup.

A. Optimum Flux Reference

Controlling motors away from their nominal operating point depreciates their efficiency. Therefore, the flux should be adjusted according to the load variations below the nominal value for optimal performance [11]. Three control methods have been proposed for doing this kind of adjustment: flux control as a function of torque [10], flux control based on loss model [12], and flux control by a minimum loss search controller [11, 13].

However, it is not intended here to employ a flux controller to minimize losses but to select an optimal flux reference based on the torque reference value. Indeed, the decrease in torque during the zero switching state depends on both the stator flux magnitude and the frequency. In detail, because of a nonlinear dependence between the motor dynamics and the rotor speed, there have been observed different behaviors at low and high speed operation [5]. At low speed, the torque increasing vectors are more effective than the torque reducing vectors for changing the torque. Conversely, the torque increasing vectors are far less effective than the torque reducing vectors at high speed. On the other hand, a very high torque ripple occurs due to both these behaviors if the sampling frequency is too low. However, increasing the sampling frequency in order to adequately compensate the ripples deteriorates the computational efficiency to a great extent.

Therefore, to minimize the torque ripple (as a main objective of our project besides saving high computational efficiency,) the torque decrement during zero state must be kept to its minimum; for the reason that, the specific application requires a DTC drive at high speed range. This can be done by applying a sufficiently large reference flux to generate the required reference torque. This will decrease the reactive power consumption as well. The following equation enables calculating such an optimal flux reference based on the torque reference value [14].

$$\begin{aligned} \left|\varphi_s^*\right|^2 &= \frac{\left[\frac{R_r}{s}\left(L_{s1}+\frac{3}{2}L_{sm}\right)\right]^2+\left[\omega_s\left(L_{r1}\left(L_{s1}+\frac{3}{2}L_{sm}\right)+\frac{3}{2}L_{sm}L_{s1}\right)\right]^2}{\frac{3}{2}p\frac{R_r}{s\omega_s}\left(\omega_s\frac{3}{2}L_{sm}\right)^2}T^* \\ &= C \times T^* \end{aligned} \tag{3}$$

B. Fuzzy Logic-Based Ripple Minimization

A voltage vector is applied for the entire switching period in the basic DTC scheme. The resulting voltage duty ratio causes the torque exceeds its reference value almost near the beginning the cycle, provoking a high torque ripple. The idea of fuzzy logic-based torque ripple minimization is to determine the duration for which each torque increasing vector is applied

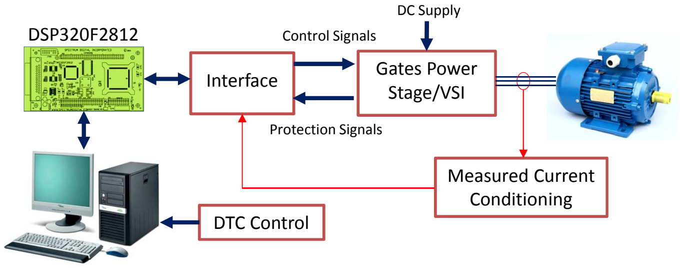


Figure 3. Schematic diagram of the experimental setup.

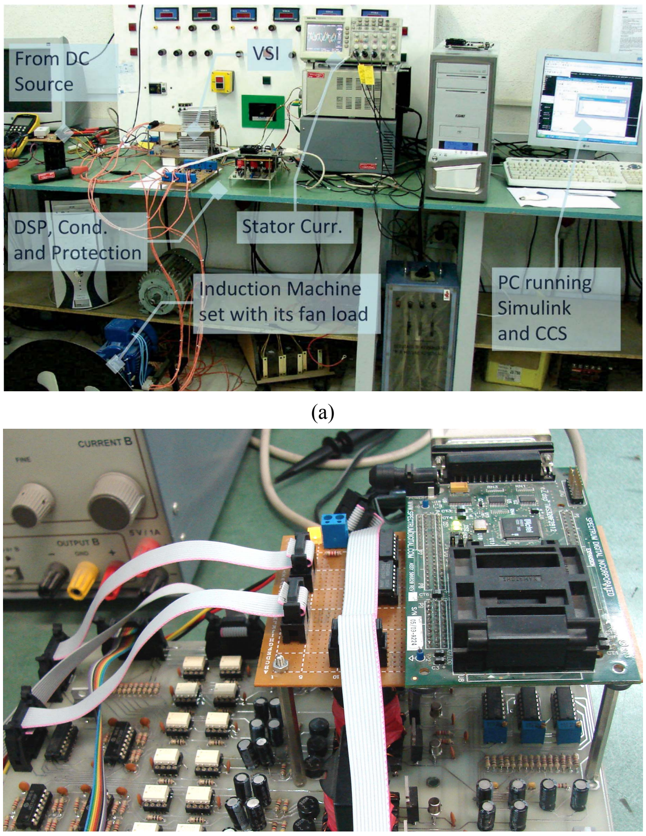
TABLE II. SPECIFICATIONS OF INDUCTION MOTOR

Rated power	1.8 kW
Rated speed	2820 rpm (@50Hz)
Rated voltage	400 V_{RMS}
Number of pair poles	$p = 1$
Stator resistance	$r_s = 6.0\ \Omega$
Stator inductance	$L_{ls} = 32.0$ mH
Rotor resistance	$r_r' = 4.9\ \Omega$
Rotor inductance	$L_{lr}' = 32.0$ mH
Magnetization inductance	$L_m = 340.0$ mH
Total inertia	$J = 0.0072$ Kgm^2
Friction coefficient	$b = 0.0054$ Kgm^2/s

in anticipation of the torque error would be minimized. As with the basic DTC, a look up table (just like Table I,) determines the most appropriate torque increasing vector to apply. This vector is then applied for a proportion of the sampling period determined by the fuzzy controller. The rest of the switching period a null state is selected which won't almost change both the torque and the flux [5]. In this way, the average inverter output voltage can take a somehow continuous range of values rather than the seven discrete voltages found in conventional DTC.

The relationship between the optimal duty ratio per sampling period and the working point (i.e. the motor's torque and speed) is non-linear. Therefore, it is more practicable to perform a duty-ratio control every switching period by using a fuzzy controller [6]. In [4], a fuzzy logic-based DTC has been proposed in which the hysteresis torque controller provides only two discrete values and the zero state is launched by the fuzzy rules. Also, in addition to this conventional fuzzy logic controller, a so-called "adaptive block" has been introduced that becomes active when the two sequentially selected states are same; and its objective is to put an increment or decrement in the previous duty cycle in order to minimize the torque ripple.

The theoretical background and fuzzy rules is employed according to [4] in this paper. Also, it has been used the fuzzy method in parallel with an optimal flux reference for implementing a high speed induction motor DTC drive system. The use of an optimal flux reference complements the torque ripple reduction by fuzzy duty ratio controller; given that a smaller decrease in torque ripple can be achieved at high speed by exclusively using the fuzzy controller [5]. Some practical experiences are as follows in the next section.



(a)

(b)

Figure 4. (a) The workstation, and (b) The main processor, DSP, and a part of the signal adaptation and the drivers board..

IV. SIMULATION AND EXPERIMENTAL RESULTS

Simulation and experimental tests have been carried out in order to verify the practical usability of the implemented setup. The experimental setup (as shown in Figs. 3 and 4) is based on an induction motor according to Table II, IGBT-VSI, and a PC/digital signal processor (the platform eZdsp based on the fixed point 32 bit DSP TMS320F2812 from TI) as a CPU, where the PC is the host and the DSP the main processor. The complete drive control system is discrete. It is developed using tools from Sim Toolbox of Simulink, and is converted in C via Code Composer Studio.

The Simulink simulation sampling time of 5 μs for the DTC control routines has been selected for simulation and sampling time of 180 μs has been selected for experiments. The results obtained from the reported project are illustrated in Figs. 5-10. A magnified view of a torque step change from 2 to 15 N.m is shown in Fig. 5. The corresponding experimental examination of a torque response identical to Fig. 5 is illustrated in Fig. 6. There is a good match between the simulated and experimented change in the reference torque. The satisfactory torque ripple is verifiable from this figure as well. To further examine the operational characteristics, it is shown the magnitude of the stator current during the torque change of Fig. 6 in Figs. 7 and 8, from the simulation and experimental setup, respectively. These two results also illustrate an identical behavior.

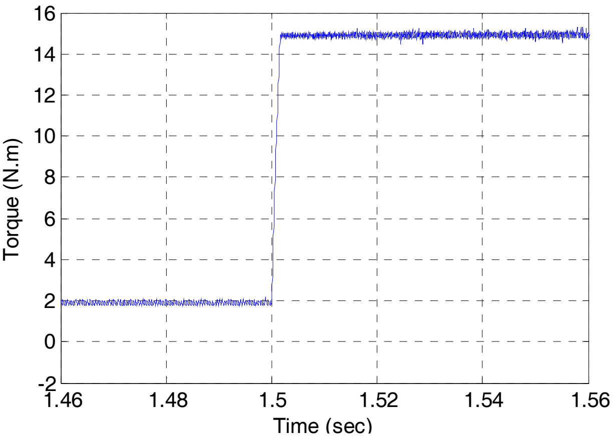


Figure 5. A magnified view of a torque step response.

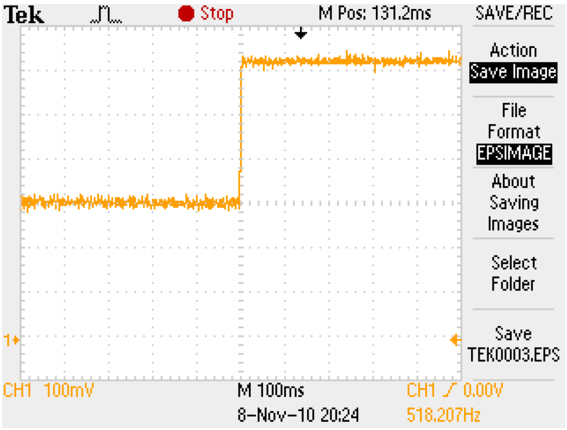


Figure 6. Experimental behavior of a torque step response corresponding to the change in Fig. 5 (4 N.m/div.)

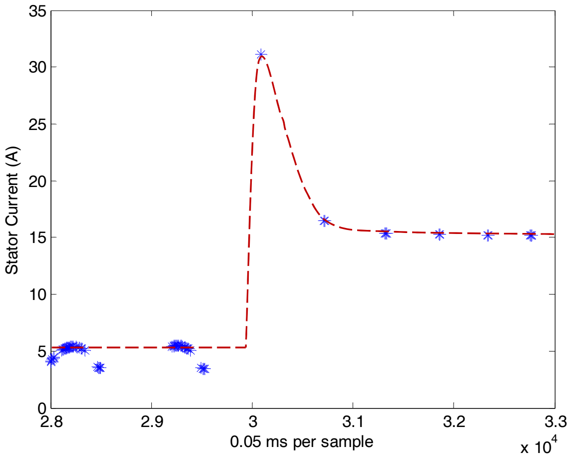


Figure 7. The magnitude of the stator current during the torque change of Figs. 5 and 6 (250ms).

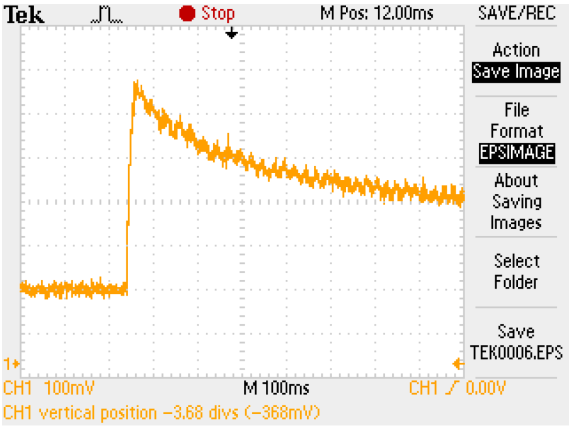


Figure 8. Experimental behavior of the magnitude of the stator current during the torque change of Fig. 6 (5 A/div.)

V. CONCLUSIONS

This paper is an implementation report of a part of a research project. The main plan was to set up a fast-processing DTC for an induction motor with an emphasis on reducing the torque ripple at high speed range. After presenting a general outline on selecting the suitable method from previously fully-established methods, a fuzzy logic-based scheme in parallel with an optimal flux reference was preferred and implemented. The results illustrated satisfactory performance. As the proposed approach is based on fuzzy logic, it is easy to implement and does not require much computational time. It should be mentioned that the whole procedure of this paper is based on expert knowledge.

REFERENCES

[1] D. Casadei, F. Profumo, G. Serra, and A. Tani, "FOC and DTC: two viable schemes for induction motors torque control," IEEE Trans. Power Electron., vol. 17, no. 5, pp. 779-788, Sep. 2002.

[2] S. A. Mir, S. Zinger, and M. E. Elbuluk, "Fuzzy controller for inverter fed induction machines," IEEE Trans. Ind. Applicat., vol. 30, pp. 78–84, Jan./Feb. 1994.

[3] P. Z. Grabowski and F. Blaabjerg, "Direct torque neuro-fuzzy control of induction motor drive. DSP implementation," in Conf. Rec. IECON'98, Aachen, Germany, Aug.–Sept. 31–4, 1998, pp. 657–661.

[4] L. Romeral, A. Arias, E. Aldabas, and M. G. Jayne, "Novel direct torque control (DTC) scheme with fuzzy adaptive torque-ripple reduction," IEEE Trans. Ind. Electron., vol. 50, no. 3, pp. 487-492, Jun. 2003.

[5] I. G. Bird and H. Zelaya De La Parra, "Fuzzy logic torque ripple reduction for DTC based AC drives," Electron. Letters, vol. 33, no. 17, pp. 1501-1502, Aug. 1997.

[6] P. Vas, "Artificial-intelligence-based electrical machines and drives. Application of fuzzy, neural, fuzzy-neural, and genetic-algorithm-based techniques," Oxford University Press 1999.

[7] A. Arias, J. L. Romeral, E. Aldabas, and M. G. Jayne, "Fuzzy logic direct torque control," Proc. IEEE Int. Symp. Ind. Electron., pp. 253–258, 2000.

[8] C. A. Martins, T. A. Meynard, X. Roboam, and A. S. Carvalho, "A predictive sampling scale model for direct torque control of the induction machine fed by multilevel voltage-source inverters", The Eur. Phys. J. Appl. Physics. EDP Sciences 1999.

[9] D. Casadei, G. Serra, A. Tani, and L. Zarri, "Assessment of direct torque control for induction motor drives," Bull. Pol. Ac.: Tech., vol. 54, no. 3, pp. 237-254, 2006.

[10] I. Takahashi and T. Noguchi, "A new quick-response and high efficiency control strategy of an induction motor," IEEE Trans. Ind. Appl., vol. IA-22, no. 5, pp. 820–827, Sep./Oct. 1986.

[11] S. Kaboli, M. R. Zolghadri, and E. Vahdati-Khajeh, "A Fast Flux Search Controller for DTC-Based Induction Motor Drives," IEEE Trans. Ind. Electron., vol. 54, no. 5, pp. 2407-2416, Oct. 2007.

[12] I. Kioskeridis and N. Margaris, “Loss minimization in induction motor adjustable speed drives,” IEEE Trans. Ind. Electron., vol. 43, no. 1, pp. 226–231, Feb. 1996.

[13] I. Kioskeridis and N. Margaris, “Loss minimization in scalar-controlled induction motor drives with search controllers,” IEEE Trans. Power Electron., vol. 11, no. 2, pp. 213–220, Mar. 1996.

[14] A. Arias, “Improvements in direct torque control of induction motors,” Ph.D. dissertation, Electron. Eng. Dept., Technical Univ. Catalonia, Terrassa, Spain, 2000.