High Performance Direct Torque Control of Induction Motors

Abdelnasser A. Nafeh, and M. M. A. Salama*, Fellow, IEEE*

Abstract—**Direct torque control (DTC) of induction machines is known to have a simple control structure with comparable performance to that of the field-oriented control technique. Two major problems that are usually associated with DTC drives are: 1) switching frequency that varies with operating conditions and 2) high torque and flux ripples. To solve these problems, and at the same time retain the simple control structure of DTC, a constant switching frequency torque controller is proposed to replace the conventional hysteresis-based controller. In this paper, the modeling of proposed controller followed by simulation and experimental results are presented. The proposed controller is shown to be capable of reducing the torque and flux ripples and maintaining a constant switching frequency**

Index Terms—**Direct torque control, constant switching frequency, induction motor, SVPWM inverter.**

I. INTRODUCTION

INDUTION MOTOR has found wide range of industrial applications due to its reliability, simple construction, ruggedness, maintenance free, and relatively low cost compared to other machines. Direct torque control (DTC) strategy was introduced by Takahashi [1] to give a fast and good dynamic performance and can be considered as an alternative to the field oriented control (FOC) strategy [2]. Therefore, in recent years the industrial application areas of the high performance AC drives based on DTC technique have gradually increased due to the following advantages over the field oriented control technique, such as:(i) Excellent dynamic performance. (ii) precise and quick control of stator flux and electromagnetic torque. (iii) absence of co-ordinate transformation, which reduce the complexity of algorithms involved in FOC. (iv) robust against machine parameters variations. (v) no current control loop. (vi) and the simplicity of the algorithm [3,4]. A classical DTC drive system, which is based on a fixed hysteresis bands for both torque and flux controllers, suffers from a varying switching frequency, which is a function of the motor speed, stator/rotor fluxes, and stator voltage; it is also not constant in steady state. Variable switching frequency is undesirable. At low speed, an appreciable level of acoustic noise is present, which is mainly due to the low inverter switching frequency. The high frequency is limited by the switching characteristics of the power devices. Therefore, there will be large torque ripples and distorted waveforms in currents and fluxes. In order to improve the dynamic performance of the classical DTC, a new modified DTC with a space vector modulator (SVM), and fuzzy logic controller (FLC) is proposed. The use of SVM is to ensure a constant switching frequency and the use of FLC is to obtain a decoupled control between flux and torque. The present paper deals with the development of a Fuzzy Logic Direct Torque Controller (FLDTC) that is expected to improve the dynamic performance compared to the classical DTC system. The study will cover the possible ways to overcome the disadvantages of the classical DTC method such as, starting problems, distorted current waveforms, variable switching frequency, and existence of high torque pulsation and flux ripple. This new DTFC system is firstly designed and proved by means of simulations. Later in the paper, experimental implementation is discussed and the results are presented. Therefore, the development of this novel induction motor controller can be separated into the following contributed steps: First, Study the classical DTC disadvantages and suggestion of new scheme to overcome them. Second, investigate of a complete dynamic model of the drive systems, relevant controllers, and its dynamic performance using MATLAB-SIMULINK and FUZZY LOGIC toolboxes. Third, implementation of an actual drive system based on low cost micro controller and suggested DTFC to validate its performance practically. Several solutions have been proposed to keep constant switching frequency, like in [2-8,18,24,25,30,32,33,35]. The hysteresis regulators are difficult to be implemented in a discrete form even a high sampling causes errors in torque regulation. The approach proposed in Ref. [17] replaces the hysteresis regulators with a discrete regulators. The control scheme based on back emf estimation. It gives better results, but the sampling time in structure still very high, computationally extensive, and parameter sensitive. The approach proposed in Refs. [23,27,28] gives good torque response and also, very low torque distortions in steady state, but the fuzzy structure of this regulators is very complicated due to many member ship functions, specially in flux angle fuzzification. This leads to a lot of fuzzy rules, which need a large memory and complicated software to be implemented. In Ref. [4] the influences of the hysteresis bands on the DTC of an induction motor are analytically investigated, and the inverter switching frequency is predicted. A new approach of DTC based on space vector modulator SVM and two PI controllers is presented in Ref. [25] which provides a constant inverter switching frequency and significantly reduction of torque and speed ripple. Ref. [35] gives a constant inverter switching frequency, but it replaces the two PI controller of the above approach Ref. [25] with a two fuzzy controller and replaces the space vector modulation SVM block by a sinusoidal PWM one. The simulation results give a significant reduction of torque ripples. But, this approach did not indicates any experimental results, and needs a coordinate transformations from synchronous reference frame to stationary reference frame then to a, b, c frame which is complicated and time consuming in programming. There are two issues and problems in motion control. One is to make the resulting system of controller and plant robust against parameter variations and disturbances. The other is to make the system intelligent. This is possible with advanced control theory such as, Neural networks, Fuzzy logic, or Neuro-fuzzy. A new control strategy in discrete DTC based on adaptive Neuro-Fuzzy structure is presented in [2,5,8]. This approach gives fast and good dynamic performance. However, the system is based on two Digital Signal Processors DSPs, the first (main) processor implements the direct torque Neuro-Fuzzy control algorithm, whereas the second provides the vector modulation which make the drive system more complicated in interfacing and programming, and costly to be implemented. The analysis on the effects of both flux and torque hysteresis bands on DTC drive system performance is presented in Ref. [4]. It is to be noted that small flux hysteresis bands leads to sinusoidal current waveforms, while small torque hysteresis bands allow smoothed torque to be generated. On the other hand, small hysteresis bands determine high switching frequency thereby increasing the switching losses. To improve the stator fluxes estimation in steady state for DTC of induction motor, a phase and magnitude compensation for the voltage model based stator flux estimator with low pass filter is proposed in Ref. [31]. Significantly improved waveforms of flux and torque are obtained. The duty cycle value based on fuzzy logic is presented in Refs. [14,34]. By varying the duty cycle between its extreme values, it is possible to apply any voltage value to the motor. Therefore, the duty cycle has to be determined for each sampling period. However, this approach still uses the two-hysteresis controllers also the torque and flux waveforms still have distorted waveforms and a high computational effort are needed. A new hybrid fuzzy controller for DTC based induction motor drives is presented in Ref. [29]. The approach satisfies a significantly improvement in steady state torque and flux ripples. However, it still uses the look-up table of classical DTC also; the drive system has a variable switching frequency. A classical DTC Drive system, which is based on a fixed hysteresis bands for both torque and flux controllers, suffers from a varying switching frequency, which is a function of a motor speed, stator, rotor fluxes, and stator voltage; it is also not constant in steady state. At low speed, an appreciable level of acoustic noise is present, which is mainly due to the low inverter switching frequency. Thus there will be a varying device switching frequency. Variable switching frequency is undesirable and is limited by the thermal condition of the switching devices and maximum switching frequency of the devices. Therefore, there will be a large torque ripples and distorted waveforms in currents and fluxes. Several solutions have been proposed to keep constant switching frequency, like in [2-5]. In order to improve the performance of the classical DTC, a new modified DTC with a space vector modulator (SVM), and fuzzy logic controller (FLC) is proposed. The use of SVM is to ensure a constant switching frequency and the use of FLC is to obtain a decoupled control between flux and torque. To achieve our goals a mathematical modeling of the classical and proposed DTFC drive systems are obtained.

II. MATIMATICAL MODELING OF SQUIRREL CAGE INDUCTION MOTOR

In order to analyze the DTC drive in terms of its switching frequency and torque ripples, the following induction machine equations written in the stationary reference frame called $\alpha - \beta$ dynamic model of the squirrel cage induction motor based on state space equations [36,37] with the reference frame fixed to the stator is given by the first order differential equations:

$$\frac{d}{dt}\begin{bmatrix} i_{s\alpha}^{s} \\ i_{s\beta}^{s} \\ i_{r\alpha}^{s} \\ i_{r\beta}^{s} \end{bmatrix} = \frac{1}{L_\sigma^2}\left(\begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix}\begin{bmatrix} v_{s\alpha}^{s} \\ v_{s\beta}^{s} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -R_s L_r & \omega_r L_m^2 & R_r L_m & \omega_r L_r L_m \\ -\omega_r L_m^2 & -R_s L_r & -\omega_r L_r L_m & R_r L_m \\ R_s L_m & -\omega_r L_s L_m & -R_r L_s & -\omega_r L_r L_s \\ \omega_r L_s L_m & R_s L_m & \omega_r L_r L_s & -R_r L_s \end{bmatrix}\begin{bmatrix} i_{s\alpha}^{s} \\ i_{s\beta}^{s} \\ i_{r\alpha}^{s} \\ i_{r\beta}^{s} \end{bmatrix}\right) \quad (1)$$

Where $L_\sigma = \sqrt{L_s L_r - L_m^2}$

$$\omega_r = \frac{Poles}{2}\omega_m \qquad rad/\sec$$

and the electromagnetic torque equation in the stationary reference frame:

$$T = \left(\frac{3}{2}\right)\left(\frac{Poles}{2}\right)\left(\lambda_{S\alpha} i_{s\beta} - \lambda_{S\beta} i_{s\alpha}\right) \quad (2)$$

III. REVIEW OF CLASSICAL DTC STRATEGY

The basic idea of DTC is when the torque is wanted to be increased, a voltage vector which increases the angle between the air gap flux linkage and the stator flux linkage is selected, and vice versa. A block diagram of a classical DTC system for an induction motor is shown in Fig.1. Two independent hysteresis (bang-bang) controllers control the motor torque and stator flux [1,8]. Therefore, the selection of hysteresis band control range will affect on the performance of the drive system [4]. The inverter switching patterns are generally directly as a function both of the torque error and of the flux error. By using only current and voltage measurements, it is possible to estimate the instantaneous stator flux and output torque. An induction motor model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period.

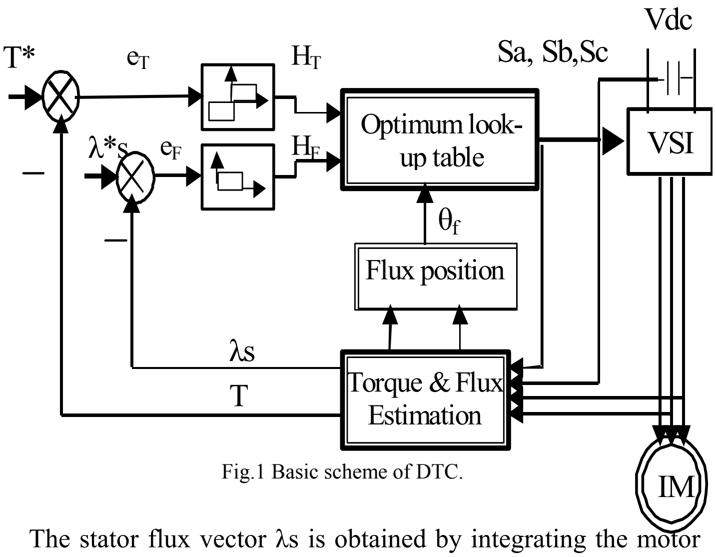


Fig.1 Basic scheme of DTC.

The stator flux vector λs is obtained by integrating the motor emf space vector, measured stator currents, and stator resistance.

$$\overline{\lambda}_s = \int \left(\overline{V}_s - R_s \overline{I}_s\right) dt \qquad (3)$$

The stator voltage space vector is calculated using the dc-link voltage Vdc and the gating signals (Sa, Sb, Sc) instead of direct measuring with Hall effect voltage sensors.

$$\overline{V}_s = \frac{2}{3} V_{dc}\,[S_a + aS_b + a^2 S_c] \qquad (4)$$

$$where\ ,\ a = e^{j\frac{2\pi}{3}}$$

The stator current space vector is calculated from measured stator currents.

$$\overline{I}_s = \frac{2}{3}[i_a + ai_b + a^2 i] \qquad (5)$$

From Fig. 1. The inputs to the switching table block are the torque and flux error, and the stator flux angle information are used to select the suitable switching pattern. Many voltage selection strategies can be utilized as widely discussed in Refs. [2-13].

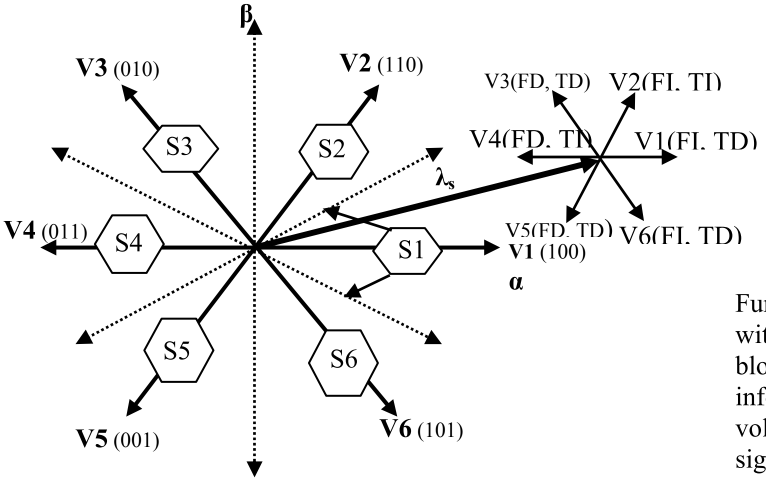


Fig. 2. Stator flux vector locus and different possible switching voltage vectors lies in sector 1.
F = Flux, T = Torque, D = Decrease, and I = Increase.

Each strategy affects the drive performance in terms of torque and current ripple, switching frequency, and torque response [4,10]. From Fig. 2. In order to increase the stator flux magnitude it is necessary to select the voltage vector that determines a high radial component along the direction of the stator flux vector λs. On the other hand, if it is need to increase the torque, it is necessary to select the voltage vector that determines the highest tangential component along the direction of stator flux vector λs [4-7]. The selection table proposed by Takahashi [1] is used as shown in Table 1.The sectors of the stator flux space vector are denoted from S1 to S6. The hysteresis controller for flux can take two different values, while the torque hysteresis controller can take three different values.

Table 1. Optimum selection table for DTC.

H$_F$	H$_T$	S1	S2	S3	S4	S5	S6
1	1	V2	V3	V4	V5	V6	V1
1	0	V7	V0	V7	V0	V7	V0
1	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
0	0	V0	V7	V0	V7	V0	V7
0	-1	V5	V6	V1	V2	V3	V4

The zero voltage vectors V0 and V7 are selected when the torque error is within the given hysteresis limits i.e. (in case of no change).

IV. PROPOSED DTC STRATEGY

The proposed scheme is shown in Fig. 3., which shows the replacement of the two hysteresis controllers of the classical DTC scheme with a fuzzy logic controller (FLC).

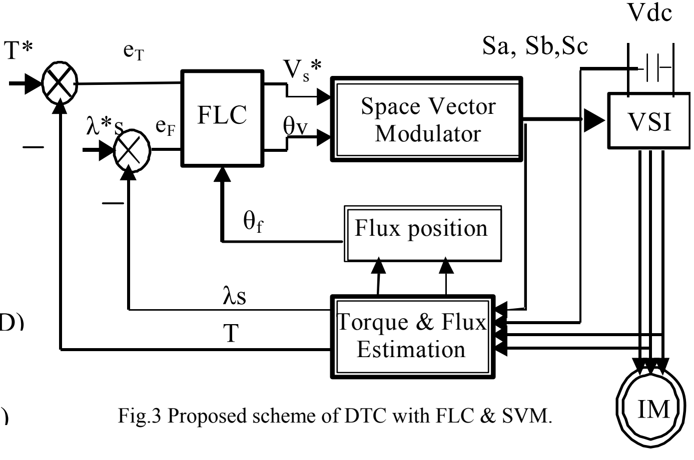


Fig.3 Proposed scheme of DTC with FLC & SVM.

Furthermore, it shows the replacement of the look-up table with a space vector modulator (SVM). The inputs to the FLC block are torque error e$_T$, flux error e$_F$, and the stator position information. The outputs of the FLC are the desired space voltage vector V_s^* and its position angle θv. These two signals (V_s^* , θv) are used to be input to the SVM block, which in turn generates the suitable gatting signals (Sa,Sb,Sc) to drive the inverter at a constant switching frequency. The will-known disadvantages of the classical DTC such as [2-4]: Variable switching frequency, current and torque distortion due to sector changes, start and low speed operation problems, and the high sampling frequency needed for digital implementation of hysteresis controllers. All the above difficulties can be overcome with the use of the modified DTC scheme. Therefore, a constant inverter switching frequency, a torque ripple reduction, and a good dynamic performance can be obtained.

V. FUZZY LOGIC CONTROLLER (FLC)

Fuzzy logic, neural networks, and genetic algorithms belong to the area of artificial intelligence. The artificial intelligence is basically using human intelligence in a computer, so that the computer can perform intelligently like a human. Moreover, FLC is recently finding wide popularity in various industrial applications. The principal structure of the FLC includes fuzzification, knowledge base, inference engine, and defuzzification. To simplify the simulation and hence the implementation, a triangular membership function sets is used for a torque error and for a flux error like in Fig. 4.

5.1. FUZZIFICATION PROCESS

The fuzzification process performs a scale transformation (input normalization) and converts the crisp input values of the process state variables into a suitable linguistic values (label).

5.2. KNOWLEDGE BASE

It consists of a database and a rule base.

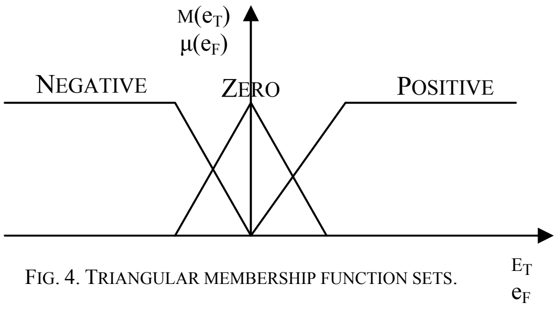


FIG. 4. TRIANGULAR MEMBERSHIP FUNCTION SETS.

5.2.1. DATA BASE

It divided to (i) choice of membership function (ii) choice of scaling factors

5.2.2. RULE BASE

The basic function of the rule base is to represent, in structured way, the control policy of an experienced process operator and/or control engineer in the form of a set of production rules, for two input single output FLC, the fuzzy IF-THEN rules assumes the form:

IF x is A and y is B THEN z is C.

Where, x, y, and z are fuzzy variables and A, B, and C are linguistic values.

5.2.3. MAIN STEPS OF FLC TUNING

- Tuning of input and output scaling factors.
- Tuning of input and output membership functions.
- Tuning of the rules to obtain optimal performance.

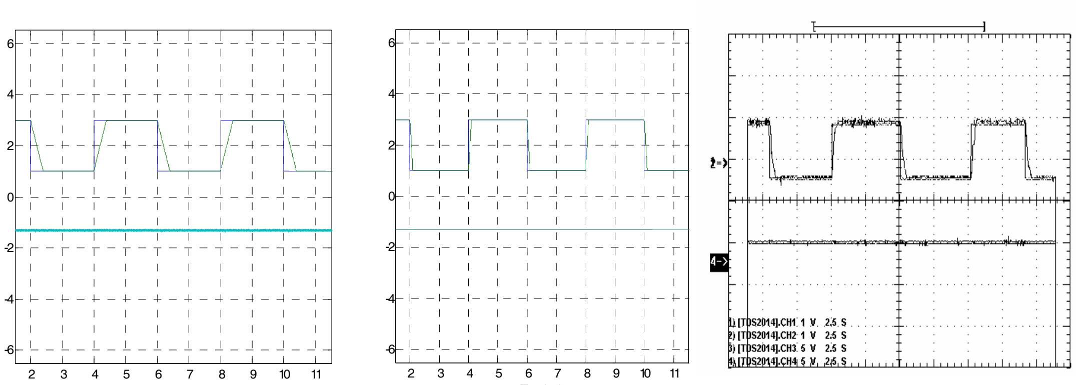
5.3. DEFUZZIFICATION PROCESS

The defuzzification process performs:

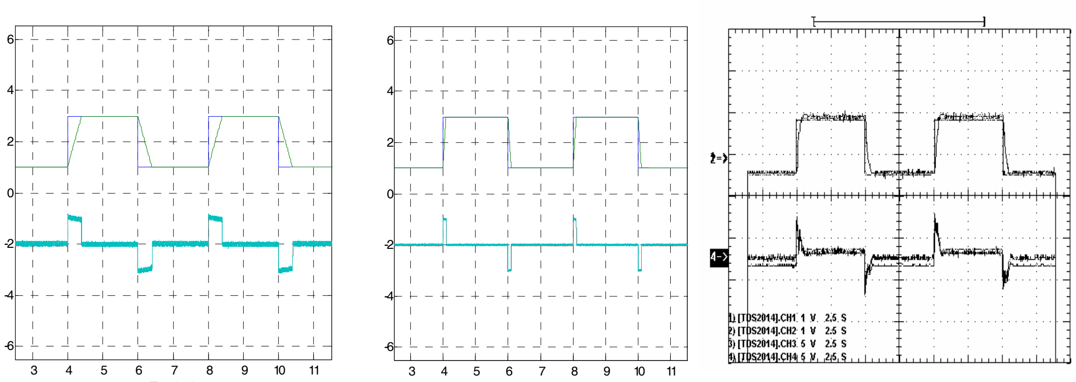
- Converts the fuzzy output value of the output variable into a single crisp value required by the process under control.
- De-normalization i.e. converts a single crisp value of the control output into its physical domain [12,,23,38,39,40].

VI. SIMULATION AND EXPERIMENTAL RESULTS

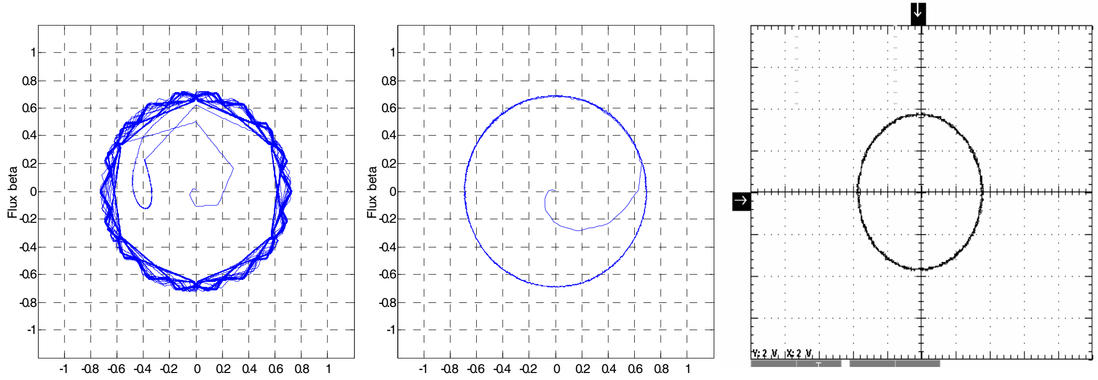
The simulation of the nonlinear drive system, in this work, is carried out using MATLAB-SIMULINK and FUZZY toolboxes. Figures 5 (a), (b), (c) and (d) show a comparison between the simulated and experimental results of classical and proposed direct torque control. The simulated classical DTC results are at the left most columns, but the simulated results of the proposed fuzzy logic DTC together with the SVM are at the middle one. The implemented system is the proposed one only and their experimental results are at the right most columns. In this section, the simulated and experimental dynamic responses of speed are compared together. The controller parameters have the same values in both cases. The theoretical and experimental results of the proposed DTC have a close correspondence between their sets of results, which verify the validity of the simulated and experimental results of the proposed DTC drive system. The speed controller parameters are adjusted to give a fast and good dynamic performance of the speed response (critically damped response). Also, the reference and estimated flux and torque responses due to the above reference speed changes are shown. The switching frequency of the simulated and experimental results is constant and equals 5 kHz for the developed algorithm. While, the simulated results of the classical DTC is at an average switching frequency of 5 kHz which corresponding to torque hysteresis bands of 2 % and flux hysteresis band of 5 % of their references respectively. Figures 5 (a) and (b) indicate that the fuzzy logic DTC together with the SVM gives faster and good dynamic response compared to the case of using the classical one. Also, the transient is better and faster for the case of using the suggested scheme. Thus, the FLC is preferable for the cases of rapidly changing. Figs. 5 (c) and (d) show the system behavior of the fluxes and currents trajectory respectively. It is noted that, the loci of both flux and current of classical one have distorted waveforms and contains a ripple in their trajectories caused by sector changes. While, the suggested scheme has a better and a good dynamic performance i.e., low torque pulsation, low flux ripple, low harmonic content in currents, no sector borders, fast flux and torque response. Note that, the classical DTC has not been realized practically, because it was



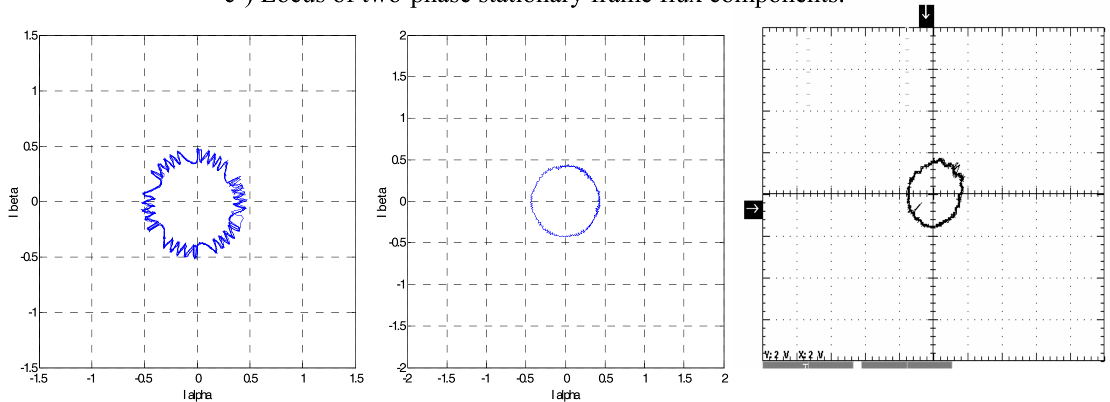
a-) Reference & actual speed and reference & actual flux.



b-) Reference & actual speed and reference & actual torque.



c-) Locus of two-phase stationary frame flux components.



d-) Locus of two-phase stationary frame current components.

Classical DTC results Proposed DTC results Exprimental DTC results

Fig. 5 A Comparison between simulated and measured results.

not possible to sample correctly the hysteresis controller. In such a way, it can be noticed that one of the advantages of the proposed fuzzy logic direct torque control together with the space vector modulator is that, the sampling time for this method can be lowered, and the whole controllers can be realized in a single processor systems.

VII. CONCLUSION

This paper introduced a new developed algorithm based on FLDTC that successfully operates even in cases of rapidly changing conditions. The complete dynamic model of the DTC system, with either of the FLC together with SVM or the hysteresis controller, is developed and simulated by using MATLAB-SIMULINK and FUZZY LOGIC toolboxes. The FLC is designed and selected to give the best transient and steady state responses and to be simple, as possible, to make its software implementation easy and to save memory usage. The MATLAB-SIMULINK and FUZZY LOGIC toolbox models established here proved to be reliable for a better understanding of the fast dynamic performance of the DTC for induction motor drive systems. The study indicates the superiority of the proposed DTC system over the classical DTC method. The simulation results confirm that the fast and good response of the proposed drive system is much better than the corresponding classical drive scheme. A fast and good dynamic response of speed or torque tracking can be achieved by controlling the switching frequency of the PWM. The switching frequency analysis introduced here confirmed the impact of the switching frequency variation on the dynamic performance of the drive system. However, one should be careful of extra high switching frequency operation because of the switching losses in the system. A comparative study between the dynamic performance of conventional and proposed DTC schemes is presented. A fast and robust speed response is obtained with the proposed controller. Despite of the switching frequency is relatively smaller, the steady state current waveforms are better than that of conventional DTC system also, there are flux and torque ripple reduction. Moreover, there are special features of DTC over the FOC method can be concluded as follows, no feed back current controllers, no traditional PWM algorithm is applied, no vector transformation as in vector control. The experimental set up including the microcontroller and the established interfacing has contributed greatly to obtain some significant experimental results for comparison with the corresponding simulation. Recorded measurements confirm that the best dynamic performance of the proposed FLDTC drive system. In this paper, a simple and low cost solution DTC scheme is suggested and implemented using a single chip and relatively low cost microcontroller of the family SAB (80C166). It is based on a fixed switching frequency of SVM and FLC. This method overcomes the disadvantages of conventional DTC scheme. The experimental result indicates very good and fast dynamic performance of the suggested scheme over the classical one. Where they indicates a constant switching frequency, a torque and flux ripple reduction, and a less current distortion. And no sector impression changes in flux trajectory as indicated previously. The reason of superior performance of the fuzzy controlled system is that it is, basically, adaptive in nature and able to realize different conditions for each input state (flux error, and torque error). Therefore, the FLC seems to be valuable controller for speed tracking of DTC systems. Also, the use of SVM is to ensure a controlled and constant switching frequency.

Direct Torque Control using Space Vector Modulation was chosen for this application based on its low current distortion and fast torque response. Its high dynamic response is due to the absence of the PI current regulator normally used in torque controllers and its low current distortion is due to the use of Space Vector Modulation to synthesis the demand motor voltage. In this paper, a novel DTC scheme is suggested. It is based on a fixed switching frequency of SVM and FLC. The performance of this control method has been demonstrated by simulations performed using Matlab / Simulink and FUZZY toolboxes. This method overcomes the disadvantages of conventional DTC scheme. The simulation results indicate a good dynamic performance of the suggested scheme over the classical one. Where they indicate a constant switching frequency, torque and flux ripple reduction, and a less current distortion.

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AUTHORS

Abdelnasser Nafeh was born in Egypt in 1971. He received his B.Sc. and M.Sc. Degrees from Benha High Institute of Technology (BHIT), Benha University, Egypt, in 1995 and 2001, respectively. He received his Ph.D. from Cairo University, Egypt, in 2005. He joined the Department of Electrical Engineering, at BHIT, Benha University, Egypt, in 1997, and is currently a lecturer at BHIT. From 2007 to 2008 he is a postdoctoral fellowship at University of Waterloo, Ontario, Canada. His research interests are in the areas of Power Electronics, Electrical Machines, Electrical Drives, Control, Fuzzy logic control, and multilevel inverters.

M. M. A. Salama (F’02) received the B.Sc. and M.Sc. degrees in electrical engineering from Cairo University, Giza, Egypt, in 1971 and 1973, respectively, and the Ph.D. degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 1977. Currently, he is a Professor in the Electrical and Computer Engineering Department, University of Waterloo. His interests include the operation and control of electric distribution systems, power-quality analysis, and insulation systems. He has consulted widely with government agencies and the electrical authority.