Direct Torque and Flux Control of Squirrel Cage Induction Motor

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***Abstract*- The paper presents a novel control method for Direct Torque and Flux Control (DTFC) of an Induction Machine (IM) fed by Space Vector Pulse Width Modulated (SVPWM) voltage source inverter. The control principle is based on Fuzzy Logic Control (FLC) and space vector modulator (SVM). The proposed robust-intelligent controller improves the low speed performance, the torque and the flux ripple and its dynamic performance of the induction machine as compared to the conventional methods of DTC.**

***Keywords-** Direct Torque and Flux Control; Constant Switching Frequency; Induction Motor; SVPWM Inverter*

I. INTRODUCTION

The modern induction machines are now replacing DC motors in industry applications, even in the applications where a fast speed and torque response in four quadrants is required. One of the reliable techniques to effectively control the speed of induction motor is the Direct Torque Control (DTC) technique proposed by Takahashi [1]. This technique can be considered as an alternative to the Field Oriented Control (FOC) strategy [2]. In recent years the use of AC drives with DTC technique have gradually increased due to its advantages over the FOC techniques: good dynamic performance, precise and quick control of stator flux and electromagnetic torque, robust against machine parameters variations, no current control loops, 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. Several solutions have been proposed to keep constant switching frequency, like in [2-8, 10-16, 25, 30, 32, 33, 34-39]. 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.

II. CONVENTIONAL 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.

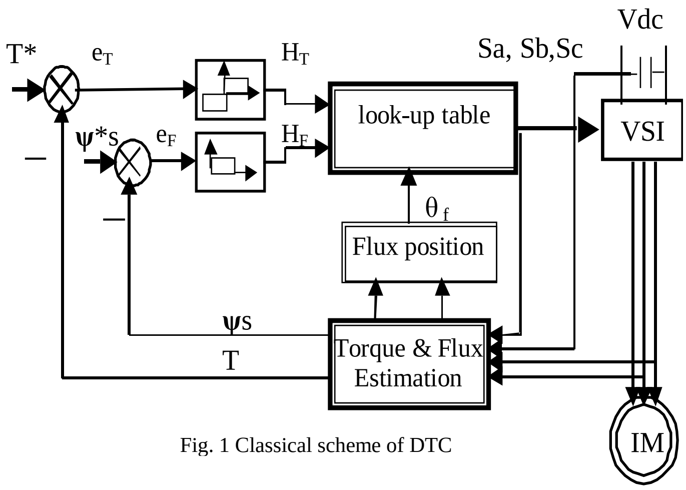


Fig. 1 Classical scheme of DTC

Two independent hysteresis (bang-bang) controllers control the motor torque and stator flux [2, 8]. Therefore, the selection of hysteresis band control range will affect on the performance of the drive system [10]. 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. 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 ref. [11, 12]. Each strategy affects the drive performance in terms of torque and current ripple, switching frequency, and torque response [10, 11]. 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 ψs. 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 ψs [10, 13]. 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.

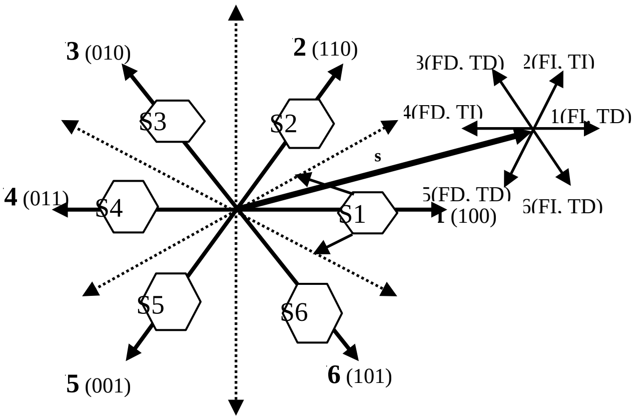


Fig. 2 Stator flux vector locus and different possible switching voltage vectors lies in sector 1
F = Flux, T = Torque, D = Decrease, and I = Increase

TABLE I TAKAHASHI 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). To achieve our goals a mathematical modeling of the classical and proposed DTFC drive systems are obtained.

III. MATHEMATICAL MODELING OF IM

The stationary reference frame labeled (α-β) dynamic model of the squirrel cage induction motor [18, 22, 26, 36, 37] with the reference frame fixed to the stator is given by:

$$\frac{d}{dt}\begin{bmatrix} i^s_{s\alpha} \\ i^s_{s\beta} \\ i^s_{r\alpha} \\ i^s_{r\beta} \end{bmatrix} = \frac{1}{L^2_\sigma}\left(\begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix} \begin{bmatrix} v^s_{s\alpha} \\ v^s_{s\beta} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -R_sL_r & \omega_r L^2_m & R_rL_m & \omega_r L_r L_m \\ -\omega_r L^2_m & -R_sL_r & -\omega_r L_r L_m & R_r L_m \\ R_s L_m & -\omega_r L_s L_m & -R_r L_s & -\omega_r L_r L_s \\ \omega_r L_s L_m & R_s L_m & \omega_r L_r L_s & -R_r L_s \end{bmatrix} \begin{bmatrix} i^s_{s\alpha} \\ i^s_{s\beta} \\ i^s_{r\alpha} \\ i^s_{r\beta} \end{bmatrix} \right) \quad (1)$$

Where

$$L_\sigma = \sqrt{L_s L_r - L^2_m}$$

$$\omega_r = \frac{P}{2}\,\omega_m$$

and the electromagnetic torque equation in the stationary reference frame:

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

Also, the dynamic equation of the motor can be written as:

$$T_e = J\frac{d\omega_m}{dt} + B\,\omega_m + T_L \quad (3)$$

For simulation and hardware minimization the stator output phase voltage of VSI can be computed from dc-link voltage and inverter switching states (Sa, Sb, Sc) instead of direct measuring with Hall effect voltage sensors as follows:

$$V_{as} = \frac{Vdc}{3}\left(2Sa - Sb - Sc\right) \quad (4)$$

$$V_{bs} = \frac{Vdc}{3}\left(2Sb - Sc - Sa\right) \quad (5)$$

$$V_{cs} = \frac{Vdc}{3}\left(2Sc - Sa - Sb\right) \quad (6)$$

Also, the two phase stationary reference frame voltages are:

$$V_{\alpha s} = V_{as} = \frac{Vdc}{3}\left(2Sa - Sb - Sc\right) \quad (7)$$

$$V_{\beta s} = \frac{V_{\alpha s} + 2V_{bs}}{\sqrt{3}} = \frac{Vdc}{\sqrt{3}}\left(Sb - Sc\right) \quad (8)$$

And for DTC modeling and implementation the stator flux vector ψ_s estimation can be calculated in stationary reference frame by integrating the motor back emf space vector, measured stator currents, and stator resistance as follows:

$$\psi_{\alpha s} = \int \left(V_{\alpha s} - R_s \, i_{\alpha s} \right) dt \qquad (9)$$

$$\psi_{\beta s} = \int \left(V_{\beta s} - R_s \, i_{\beta s} \right) dt \qquad (10)$$

$$\psi_s = \psi_{\alpha s} + j \psi_{\beta s} \qquad (11)$$

Where, the flux magnitude and its position can be determined from:

$$\left| \overline{\psi_s} \right| = \sqrt{\psi_{\alpha s}{}^2 + \psi_{\beta s}{}^2} \qquad (12)$$

$$\theta_f = \tan^{-1} \left(\frac{\psi_{\beta s}}{\psi_{\alpha s}} \right) \qquad (13)$$

By using the previous equations and the look up table the simulation of classical DTC is achieved. Unfortunately, a low speed and starting problems are exists with torque and flux ripples and variable switching frequency from hysteresis controllers which may damage and have a bad effect on the power switches of the inverters and the overall performance.

IV. ANALOG AND DIGITAL IMPLEMENTATION OF HYSTERESIS CONTROLLER

Since a DTC-based drive selects the inverter switching does not state using switching look-up table, nor is current controllers pulse width modulation required, thereby providing fast torque response. However, this switching table-based DTC approach has some disadvantages. These disadvantages are described as follows. For digital implementation, the system sampling frequency for the calculation of torque and flux should be very high to provide good tracking performance and limit the errors of the torque and the flux within the specified bands, respectively. Moreover, a large torque ripple is generated due to delay time caused by the necessary calculation time of DTC algorithms, the sluggish response of measured voltages and currents due to the Hall Effect transudes delay, and the conversion time of the analog to digital converters A/Ds [11, 14, 15, 22]. Hence, if the DTC algorithm selects the optimum inverter switching state from the switching look-up table in one sampling period, the unavoidable delay between consecutive sampling would cause increased errors of both flux and torque. Therefore, the torque and flux couldn't be restricted within the specified Hysteresis bands.

Many technical papers have concerned for improving of direct torque control performance like in [2, 5, 7, 8, 10, 13, 14, and 21]. Moreover, any digital implementation of the Hysteresis blocks introduces, an extra ripple, which depends on the sampling time (Ts) as illustrated in Fig. 3. An analog implementation would have constant ripple within its Hysteresis bands at the cost of no constant sampling time i.e. (the time between the samples is not constant) as shown in Fig. 3(a). On the contrary, in a digital implementation the time between each sample is constant but the ripple is variable and higher than the Hysteresis bands as shown in Fig. 3(b). Therefore, the digital Hysteresis block should also be represented with a sample and hold (S/H) working at the sampling frequency. In addition to the hardware delay there is also a software delay, which degraded the dynamic performance of the traditional DTC [11, 14, 15, 21].

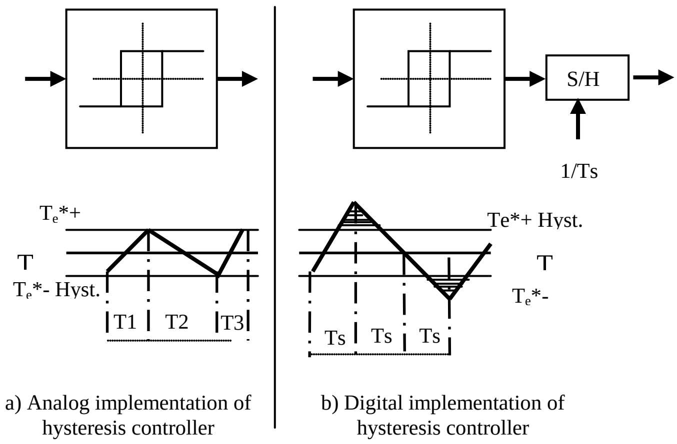


Fig. 3 Torque response for analog and digital implementation of Hysteresis controller

Alternatively, in this paper a new modified approach of DTC based on fuzzy logic and space vector modulator is presented. Fuzzy logic is introduced to make a decoupling control between the torque and flux and the SVM is incorporated with DTC for induction motor drives to provide a constant inverter switching frequency. To solve these problems, a space vector modulator SVM and Fuzzy Logic Controllers are used instead of look up table and Hysteresis controllers respectively.

V. PROPOSED DTC STRATEGY

The proposed scheme is shown in Fig. 4 which shows the replacement of the two Hysteresis controllers of the classical DTC scheme with a fuzzy logic controller (FLC). 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 flux position information θ_f. The outputs of the fuzzy logic controller (FLC) are the desired space voltage vector V_s^* and its position angle θ_v. These two signals (V_s^*, θ_v) are used to be inputs to the space vector modulator (SVM) block, which in turn generates the suitable gating signals (Sa, Sb, Sc) to drive the inverter at a constant switching frequency.

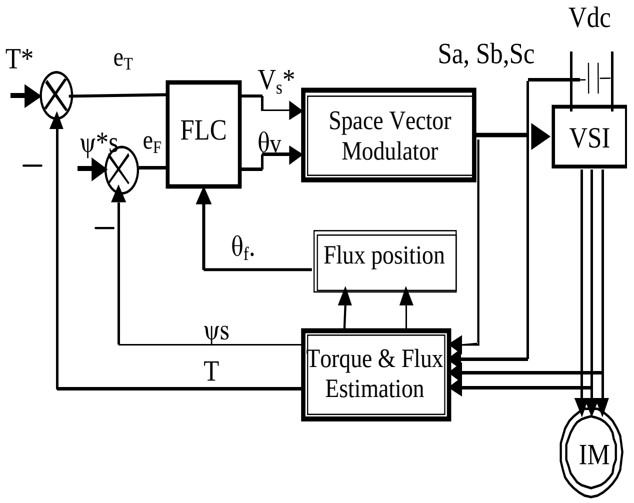


Fig. 4 Proposed scheme of dtc with FLC & SVM

The will-known disadvantages of the classical DTC such as [2-8]: 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.

VI. AN IMPROVED FLUX ESTIMATION IN DTC OF INDUCTION MOTOR

This section describes the problem associated with a pure integrator. Integration error comprises of a drift produced by the integrator, somehow related to initial condition, and the drift produced by error present in the back electromotive force (emf) due to measurement offset error in the terminal voltage or/and phase current. The performance of the induction machine control mainly depends on the accuracy of the estimated flux. The implemented method compensates the error produced by the inherent problem in the pure integrator and measurement error. This method can be easily applied in a Microcontroller-based induction machine control to estimate the stator flux. The execution time required to implement the proposed system is small that there will not be much software computation burden. This dc offset is an error that is not desired to be there and it distorts the output of the integrated signal. Attempts have been made to modify the pure integrator by implementing it using a low pass filter [10, 12, 16, 17, 18, 21]. Low pass filter will produce errors in magnitude and phase angle especially if the excitation frequency is lower than the cutoff frequency of the low pass filter. The analog method to estimate the stator flux as indicated previously given by:

$$\overline{\psi}_s = \int \left(\overline{V}_s - R_s \overline{I}_s \right) dt \qquad (14)$$

The above equation can be implemented in a discrete (digital) form as:

$$\overline{\psi}_{s\,n+1} = \overline{\psi}_{0n} + \left(\overline{V}_{sn} - R_s \overline{I_{sn}} \right) \Delta t \qquad (15)$$

As stated before, this approach will fall due to many errors in addition to a dc-offset component. A common way to implement the digital integrator is to use a first order Low Pass Filter (LPF) instead of pure integrator of the above equation. Let the stator voltage equation:

$$\overline{V_s} = R_s \overline{i}_s + p\overline{\psi_s} \qquad (16)$$

Where, p = d/dt. A low pass filter is obtained by replacing

$$\frac{1}{p} \rightarrow \frac{T}{1+pT} \qquad (17)$$

This gives us

$$p\overline{\psi_s} = \overline{V_s} - R_s \overline{i}_s - \frac{1}{T}\overline{\psi_s} \qquad (18)$$

The discrete time of the last equation is:

$$\overline{\psi}_{s\,n+1} = \overline{\psi}_{0n} + \left(\overline{V}_{sn} - R_s \overline{I_{sn}} \right) \Delta t - \frac{\Delta t}{T} \overline{\psi}_{s\,n} \qquad (19)$$

Where, Ψ_{0n} is the initial value of stator flux, $\Psi_{s\,n+1}$ is the present flux, $\Psi_{s\,n}$ is the previous value of stator flux, Δt is the sample time, and 1/ T is the cut-off frequency of the low pass filter. Note that, the low pass filter (LPF) does not, however, give very good results at frequencies lower than the cut-off frequency. The estimation of flux linkage is usually divided into separate estimation of the α**,** and β components of the stator flux linkage. Discrete time implementation of the integrator becomes:

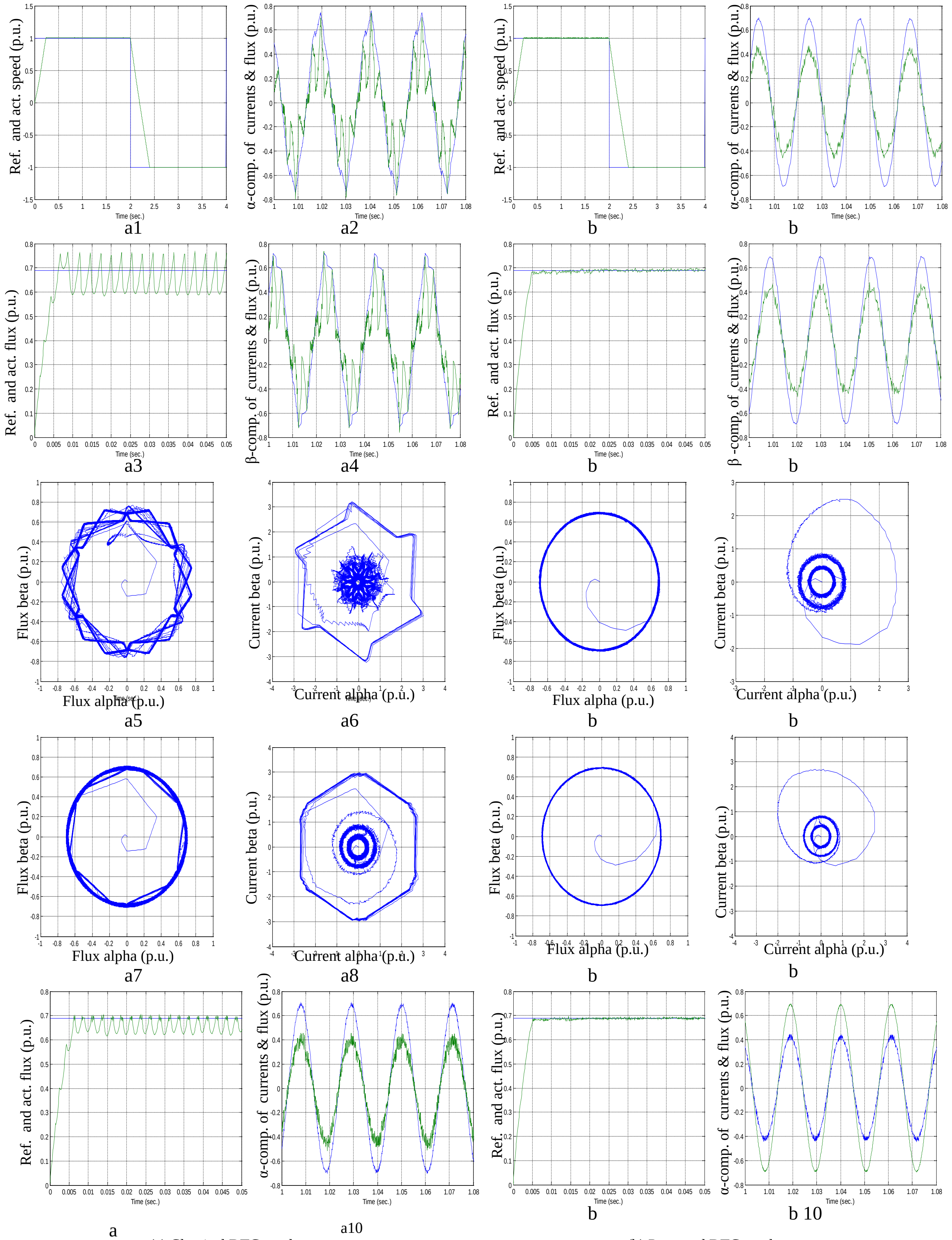
$$\overline{\psi}_{\alpha s\;n+1} = \overline{\psi}_{0\alpha n} + \left(\overline{V}_{\alpha s\,n} - R_s \overline{I_{\alpha s\,n}} \right) \Delta t - \frac{\Delta t}{T} \overline{\psi}_{\alpha s\;n} \qquad (20)$$

$$\overline{\psi}_{\beta s\;n+1} = \overline{\psi}_{0\beta n} + \left(\overline{V}_{\beta s\,n} - R_s \overline{I_{\beta s\,n}} \right) \Delta t - \frac{\Delta t}{T} \overline{\psi}_{\beta s\;n} \qquad (21)$$

By using the last two equations, the estimation of stator flux can be improved and a good dynamic performance of the proposed DTFC with good waveforms can be obtained.

VII. SYSTEM SIMULATION

The objective of this part is to illustrate the simulation of the conventional and proposed systems to consolidate the theoretical analysis of the paper. The simulation work conducted in this paper is based on, Matlab / Simulink programming and Fuzzy Logic toolbox. The simulation results of the conventional and proposed drive systems are based mainly on a 2.2kW three-phase induction motor and the previously mentioned equations. Figure 5 represents the simulation results of the complete inverter drive systems. The figure indicates that the results of classical DTC are (14) arranged from a1 to a10 also, the results of the suggested DTC are from b1 to b10 and arranged by this way for analogy and investigation between them. The classical DTC results of Fig. 5 are taken at a torque and flux Hysteresis bands of 10 % for both.



(a) Classical DTC results (b) Proposed DTC results

Fig. 5 Dynamic performances of DTC schemes with speed tracking

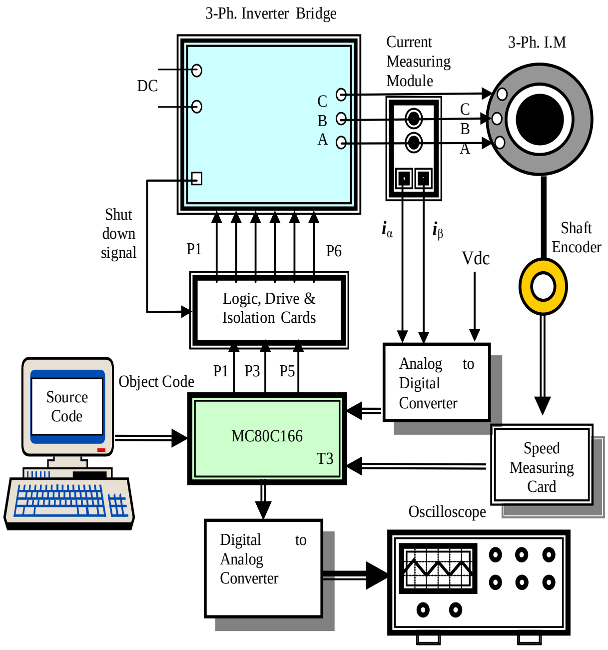


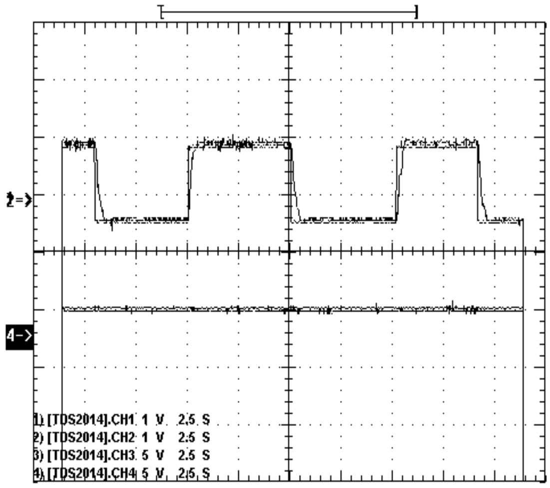
Fig. 6 Connection diagram of the implemented DTC system

These bands are nearly equivalent to an average switching frequency of 4.4 kHz. On the other hand, the proposed DTC results of Fig. 5 are taken at a constant switching frequency of 2.5 kHz. The closed loop DTC model was simulated based on the speed trajectory pattern depicted in Figs. 5 (a1) and (b1) at the same dc-link voltage, motor parameters, sampling time, and at the same reference flux to be fair-minded in our comparison and discussions. Figures 5 (a1) and (b1) confirm a very good agreement between the reference speed trajectory assumed for the DTC model and the speed response of the drive motor. The figures from a1 to a6 are taken at an average switching frequency of 4.4 kHz, while figures from b1 to b6 are taken at a constant switching frequency of 2.5 kHz. The same arrangements are obtained from the two drive systems and distributed by the same manner like in Fig. 5 but with different torque and flux Hysteresis bands and different switching frequency. The dynamic behavior of the two DTC schemes with torque and flux Hysteresis bands equals to 1 % which corresponding to an average switching frequency of 22.3 kHz for classical DTC and a constant switching frequency of 5 kHz for the proposed DTC is shown in Fig. 5. The figures from a7 to a10 are taken at an average switching frequency of 22.3 kHz, while figures from b7 to b10 are taken at a constant switching frequency of 5 kHz. It can be noticed from Figs. 5 that, when the torque and flux Hysteresis band are decrease the response of the classical DTC drive system becomes better but the average switching frequency is increased and becomes unpredictable. The unpredictable switching frequency may damage the power devices of the inverter and has a bad effect on the overall performance therefore; the switching losses are increased [2-8, 11, 13, 20]. But by using our proposed DTC drive system a controllable and lower switching frequency with a very good dynamic performance are achieved.

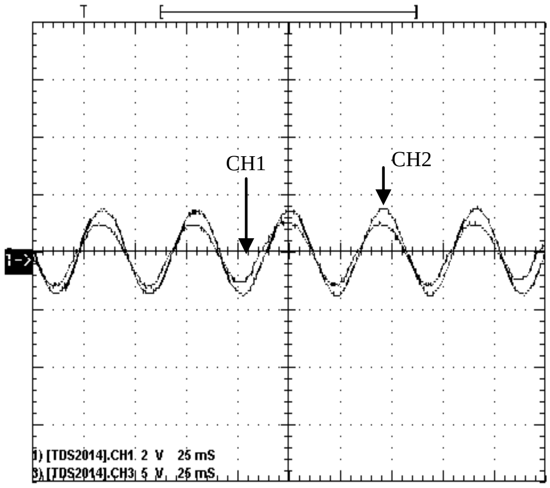
I. SYSTEM IMPLEMENTATION

The objective of this part is to illustrate the experimental set up of the implemented system to consolidate the theoretical analysis of the paper. The experimental work conducted in this paper is based on, the micro-controller variable speed cage drive system running under different conditions. Test results are compared with simulation and the necessary discussions are mentioned. The experimental results of this proposed drive system are based mainly on a 2.2kW three-phase induction motor and displayed facilities using four-channel digital storage oscilloscope 'Tektronix-TDS2014'. The results are recorded by snap shots of different examined cases and then analyzed when required. Figure 6 represents the schematic connection between the different modules in the complete inverter drive system. The figure indicates that the main elements of the experimental system arranged for this study are: the PC with the necessary software and the interfacing developed specially for this investigation, the micro-controller, family MC80C166, the data acquisition logic card acting as an interface between the micro-controller and the 3-phase inverter circuits, Hall-effect current sensors essentially to measure the actual current under any operating condition and then used to compute the (α-β) current components in the stationary (α-β) reference frame, Hall-effect voltage sensor essentially to measure the actual DC-link voltage under any operating condition and then used to compute the (α-β) voltage components in the stationary (α-β) reference frame with the aid of the switching states (Sa, Sb, and Sc), and the examined 3-phase induction motor.

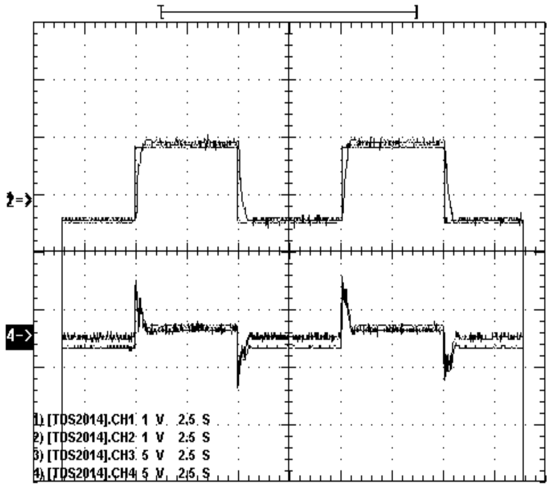
Fig. 7 shows some partial results of the proposed DTC using SVM technique and fuzzy logic controller. Figs. 7 (a) and (c) indicate that the fuzzy logic DTC together with the SVM gives faster and good dynamic response compared to the case of using the classical one. Also, the transient is better and faster for the case of using the suggested scheme. Thus, the FLC is preferable for the cases of rapidly changing. Figs. 7 (e) and (f) show the system behavior of the currents and fluxes 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 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 MC80C166 systems which is low cost solution. Figures 7 (b), and (d) indicate the two-phase direct components of current alpha and flux alpha with quadrature components of current beta and flux beta with each other. An insight view of waveforms indicates that the current alpha is nearly in phase with the flux alpha and current beta is in phase with flux beta in case of no load and steady state operation.



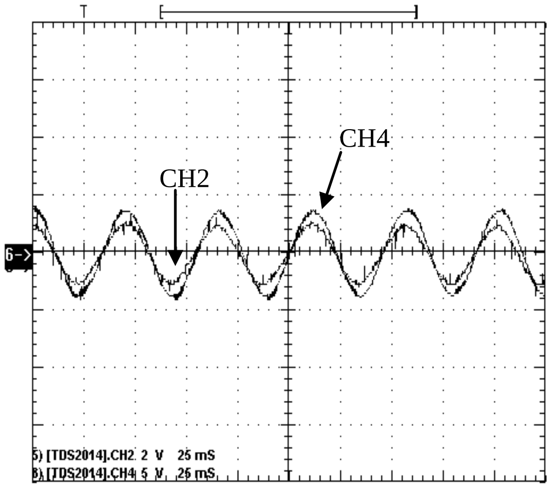
A-) Reference & actual speed and reference & actual flux



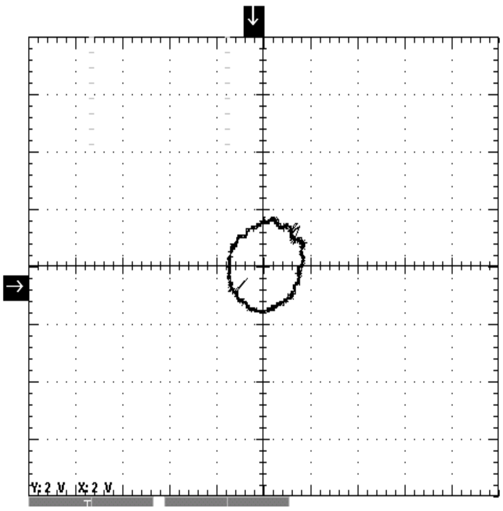
b-) i alpha and flux alpha.
(ch1 (i alpha): 0.8 p.u. /div, ch3 (flux alpha): 1 p.u. /div, & time: 25 ms / div)



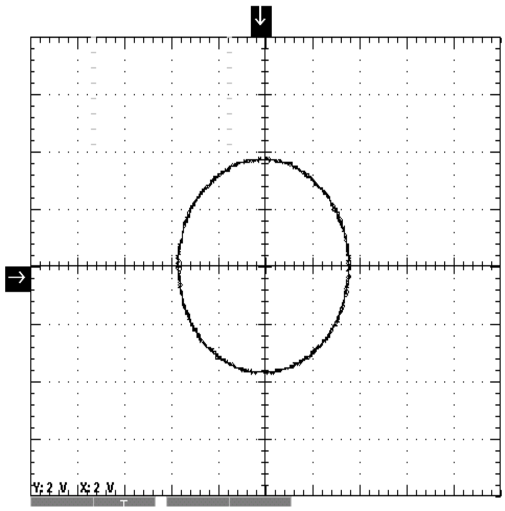
c-) Reference & actual speed and reference & actual torque



d-) I beta and flux beta.
(CH2 (I beta): 0.8 p.u. /div, CH4 (flux beta): 1 p.u. /div, & Time: 25 ms /div)



e-) Locus of two-phase stationary frame current components



f-) Locus of two-phase stationary frame flux components

Fig. 7 Experimental results of proposed DTC

Also, the direct component of current (I alpha) has a phase shift angle of 90 degree electrically with the quadrature component of flux (flux beta), and the quadrature component of current (I beta) has a phase shift angle of 90 degree electrically with the direct component of flux (flux alpha). The experimental results are performed at a constant switching frequency of 5 kHz. Then a torque and flux ripples minimization can be obtained by using the suggested scheme.

I. CONCLUTION

This paper presents a novel control method for DTFC of squirrel cage induction motor fed by a Space Vector Pulse Width Modulation voltage source inverter. The control strategy is based on fuzzy logic control and space vector modulator. The proposed controller has been tested in order to verify its behavior. The simulation and experimental results was proved that the controller ensured good response in operation near zero rotor speed and also good dynamic performance. The suggested system has a low cost price achieved by using MC80C166. From the simulations and experimental results of the proposed scheme it can be noted that a very good dynamic and steady state performance are achieved under different conditions with torque and flux ripples minimizations with constant switching frequency.

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