DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING INTELLIGENT CONTROLLER

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Abstract—The switching frequency of a conventional direct torque control (DTC) strategy which is based on hysteresis controllers results in a variable switching frequency which depends on the mechanical speed, flux, stator voltage, and the hysteresis band of the comparator. In this paper, a DTC scheme using Space vector modulator (SVM) and fuzzy logic controller (FLC) is suggested. A comparison with the classical DTC is presented. The suggested control strategy guarantees very good dynamic and steady state characteristics with low sampling rate and a constant switching frequency. The simulation results are presented to validate the scheme.

1. INTRODUCTION

Induction 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.
 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 [2,3,4,5]. 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.

2. INDUCTION MOTOR MODEL

The $\alpha - \beta$ dynamic model of the squirrel cage induction motor [6,7] with the reference frame fixed to the stator is given by:

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

$$\left. + \begin{bmatrix} -R_sL_r & \omega_rL_m^2 & R_rL_m & \omega_rL_rL_m \\ -\omega_rL_m^2 & -R_sL_r & -\omega_rL_rL_m & R_rL_m \\ R_sL_m & -\omega_rL_sL_m & -R_rL_s & -\omega_rL_rL_s \\ \omega_rL_sL_m & R_sL_m & \omega_rL_rL_s & -R_rL_s \end{bmatrix}\begin{bmatrix} i_{s\alpha}^s \\ i_{s\beta}^s \\ i_{r\alpha}^s \\ i_{r\beta}^s \end{bmatrix} \right)(1)$$

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

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

and the electromagnetic torque equation in the stationary reference frame:

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

3. 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 [9]. 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.
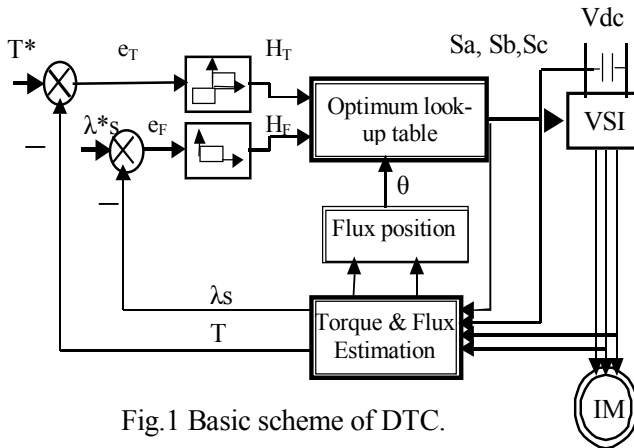

Fig.1 Basic scheme of DTC.

The stator flux vector $\overline{\lambda}_s$ 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 gatting signals (Sa, Sb, Sc) instead of direct measuring with Hall effect voltage sensors.

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

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

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

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

The motor torque is estimated from Eq. 2. 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. [10,11]. Each strategy affects the drive performance in terms of torque and current ripple, switching frequency, and torque response [9,10]. 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 $\overline{\lambda}_s$. 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 $\overline{\lambda}_s$ [9,12]. The selection table proposed by Takahashi [1] is used as shown in Table 1.
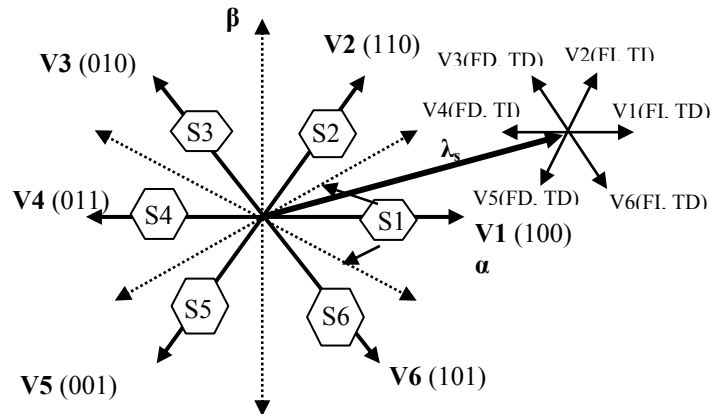

Fig. 2. Stator flux vector locus and different possible switching voltage vectors lies in sector 1.
F = Flux, T = Torque, D = Decrease, and I = Increase.

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).

4. 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). 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 θ_v .
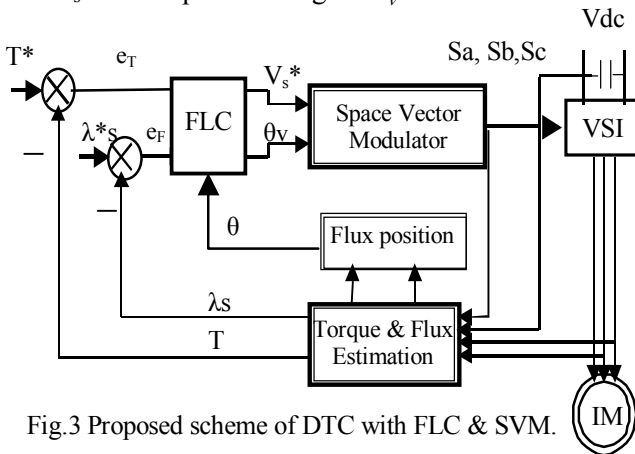
Fig.3 Proposed scheme of DTC with FLC & SVM.

These two signals (V_s^* , θ_v) 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 [2,3,4]: 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.

5. 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.
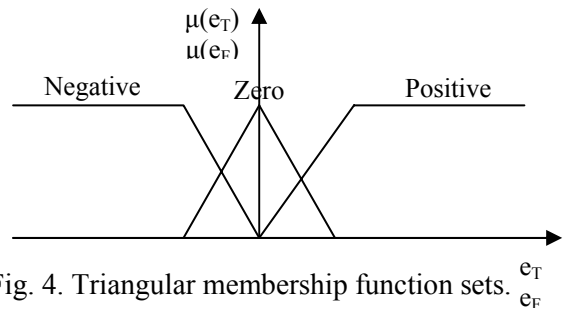

Fig. 4. Triangular membership function sets. e_T e_F

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.

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 [13,14, 15,16].
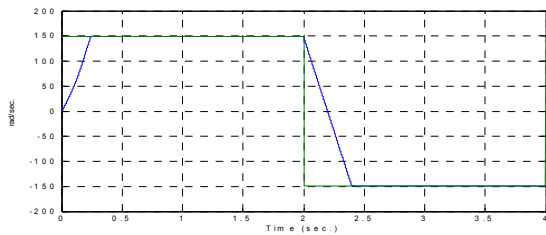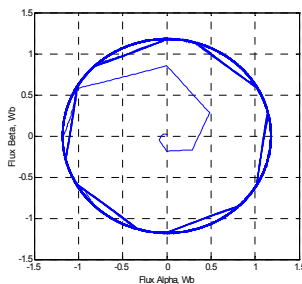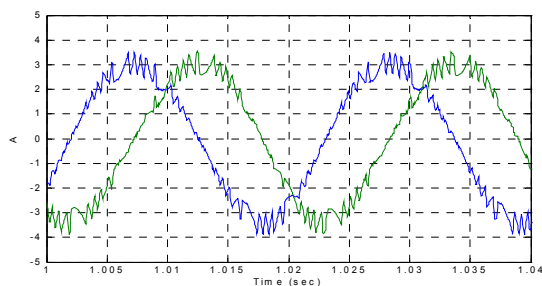
5.a) Reference & Actual speed at average 31 kHz
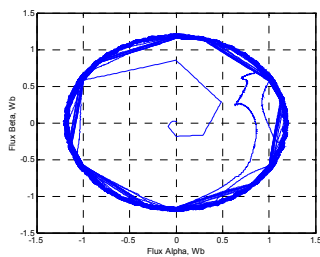

6.a) Reference & Actual speed at 5 kHz
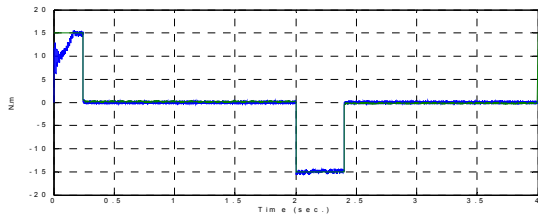
5.b) Reference & Actual torque at average 31 kHz

6.b) Reference & Actual torque at 5 kHz
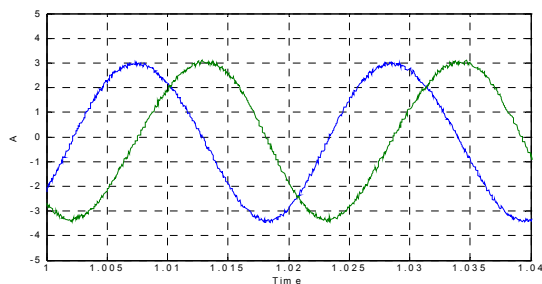
5.c) Two phase stationary currents at average 31 kHz

6.c) Two phase stationary currents at 5 kHz
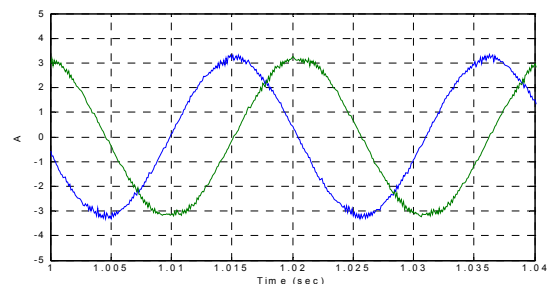
5.d) Locus of stator flux at average 31 kHz

6.d) Locus of stator flux at 5 kHz
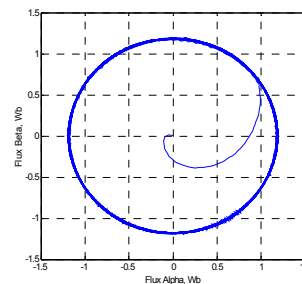
5.e) Two phase stationary currents at average 13 kHz

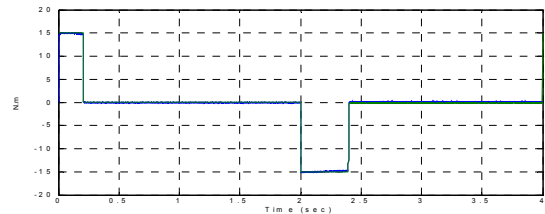6.e) Two phase stationary currents at 1 kHz
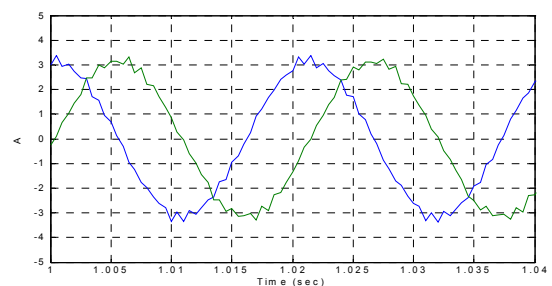
5.f) Locus of stator flux at average 13 kHz
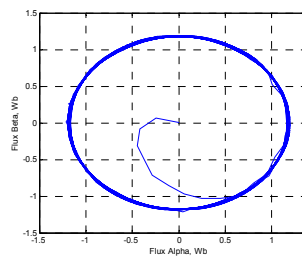
6.f) Locus of stator flux at 1 kHz

Fig. 5 Results of classical DTC

Fig. 6 Results of proposed DTC

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6. SIMULATION RESULTS

The simulation of the nonlinear drive system, in this work, is carried out using MATLAB-SIMULINK and FUZZY toolboxes. Fig. 5 shows the classical DTC results at an average switching frequency 31 kHz, corresponding to ($H_T = 0.1$ %, $H_F = 0.1$ %), and at an average switching frequency of 13 kHz, corresponding to ($H_T = 1$ %, $H_F = 2$ %). From these figures it is clear that as the hysteresis bands decrease the results are better but the switching frequency and switching losses are high. Moreover, there are torque ripples, current distortion, variable switching frequency, and sector impression changes in flux trajectory as shown in Figs. 5 (d) and (f). All these disadvantages are removed in results of the proposed scheme as shown in Fig. 6. These results are taken at two values of switching frequency (1kHz and 5kHz). Although, the switching frequency taken is low as compared to the classical one, the results are very good.

7. CONCLUSION

In this paper, a novel DTC scheme is suggested. It is based on a fixed switching frequency of SVM and FLC. The scheme is verified 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, a torque and flux ripple reduction, and a less current distortion.

APPENDIX

Parameter used for IM drive system are: 2.2 kW, VLL = 380 V delta, line current = 5.3 A, nr = 1420 rpm, Rs = 11 Ω , Rr = 3.2 Ω , Lm = 343.8 mH , Ls = 371.3 mH , Lr = 371.3 mH , Poles = 4, f =50 Hz.

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