

DTC of Twelve Sector IM Drive Using Four Level Hysteresis Control to Reduce Torque Ripple Comparing with Conventional Control

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Abstract:

In recent years, the areas of industrial application of AC drives, especially Induction machine based on DTC technique has gradually increased due to its advantages over the other techniques of control. In conventional direct torque control, the selection of flux linkage & electromagnetic torque errors are made within the respective flux and torque hysteresis bands in order to obtain fast torque response, low inverter switching frequency and low harmonic losses. However conventional DTC suffers from high torque ripple and variable switching frequency. This paper, propose a method to reduce torque fluctuations, where the circular flux vector is divided into twelve sectors and is compared with conventional DTC method where the flux vector is divided into six. The twelve sectors DTC method is simulated by using MATLAB/simulink package which represent the reduction of torque repulsions

Keywords: Induction machine, DTC, Twelve sector

I. Introduction

An electric drive is an industrial system which performs the conversion of electrical energy to mechanical energy (in motoring) or vice versa (in generator braking) for running various processes such as: production plants, transportation, home appliances, etc. Modern electrical drive systems are composed principally of motors [1], power electronics components, transformers, analog/digital controllers and sensors or observers. The improvements and the enormous advances in the field of power electronic converters technology [2] and software / implementation technology have enabled advanced and complex control techniques. With these advances and robust control algorithms improvement, considerable research effort is defined for developing optimal techniques of speed and torque control for induction machines.

The direct torque control (DTC) is one of the actively researched control schemes of induction machines, which is based on the decoupled control of flux and torque. DTC provides a very quick and

precise torque response without the complex field-orientation block and the inner current regulation loop. A Direct Torque Control (DTC) was introduced in the mid 1980s, by Takahashi and Noguchi [3], for low and medium power applications; also Direct Self Control (DSC) was proposed by Depenbrock for high power applications [4]. It is also known that DTC drive is less sensitive to parameters de-tuning (only stator resistor is used to estimate the stator flux) and provides a high dynamic performances. This type of command involves nonlinear controller type hysteresis, for both stator flux magnitude and electromagnetic torque, which introduces limitations such as a high and uncontrollable switching frequency.

This controller produces a variable switching frequency and consequently large torque and flux ripples and high currents distortion. The DTC is mostly used in the objective to improve the reduction of the flux's distortion, and to have good dynamic performances. It is essentially based on a switching table which allows selecting the vector position to apply to the inverter according to the position of the stator flux vector and of the direct control of the stator flux and the electromagnetic torque. Fig.1 shows the direct torque control method block diagram [5]

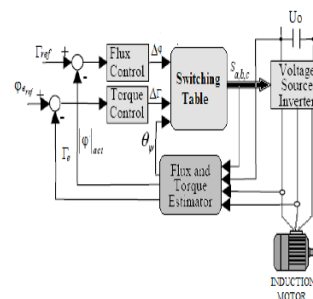


Fig. 1 Direct torque control method block diagram

The direct control method is sufficient to control with respect to changes in the machine parameters without using reverse current regulation in addition, providing fast dynamic torque response. Direct torque control method (DTC) is based on

applying a switching series, which shall directly eliminate errors, which shall occur in torque, through the reference given as value and the calculated flux, to the power switching elements in the inverter. Depending upon the magnitude of torque error and position of stator flux a better drive performance has been achieved by varying duty ratio of the selected voltage vector during each switching period [6]. To control the torque and flux directly in deadbeat Fashion voltage space vector has been calculated [7].

In conventional DTC, six sector of voltage space vector is considered of 60° band each. Every sector has two cases. This creates an uncertainty in the torque and flux within a 60° band. In order to obtain more stable switching by using all six vectors within a sector, the flux trajectory should be divided into twelve sector instead of six sector. Thus by increasing the number of sector in conventional DTC we can reduce the torque fluctuations. Two types of the conventional DTC methods and the twelve sectors DTC method are compared with respect to their torques and fluxes. It is observed that increasing the number of the sectors and changing the switching table have improved the torque and the flux.

II. Direct Torque Control

Direct Torque Control (DTC) has become an alternative to field oriented control or vector control of induction machine. It was introduced in Japan by Takahashi and Depenbrock [3]-[4]. DTC of induction machine has increasingly become the best alternative to Field-Oriented Control methods. The block diagram of DTC system for an induction motor is as shown in Fig.1. The DTC scheme comprises torque and flux estimator, hysteresis comparators for flux and torque and a switching table.

The configuration is much simpler than the vector control system due to the absence of coordinate transforms between stationary frame and synchronous frame and PI regulators. It also doesn't need a PWM and position encoder. DTC based drives are controlled in the manner of a closed loop system without using the current regulation loop. DTC scheme uses a stationary *d-q* reference frame having its *d*-axis aligned with the stator *q*-axis [8]. Torque and flux are controlled by the stator voltage space vector defined in this reference frame. The basic concept of DTC is to control directly the stator flux linkage (or rotor flux linkage or magnetizing flux linkage) and electromagnetic torque of machine simultaneously by the selection of optimum inverter switching modes. The use of a switching table for voltage vector selection provides fast response, low inverter switching frequency and low harmonic losses without the complex field orientation by

restricting the flux and torque errors within respective flux and torque hysteresis bands with the optimum selection being made. The DTC controller comprises hysteresis controllers for flux and torque to select the switching voltage vector in order to maintain flux and torque between upper and lower limit.

The benefits of DTC over traditional AC drive technology are as follows:

- Torque response
- Torque control at low frequencies
- Torque repeatability
- Motor static speed accuracy
- Dynamic speed accuracy

Stator flux is a time integral of stator EMF

$$\frac{d\psi_s}{dt} = V_s - i_s R_s \quad \text{-----(1)}$$

Selection of appropriate voltage vector in the inverter is based on stator equation in stator-coordinates

$$\Delta\psi_s = \psi_s - \psi_{s0} = \int_0^{TL} (V_s - i_s R_s) dt \quad \text{----- (2)}$$

Electromagnetic torque can be expressed as

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) \psi_s I_s \quad \text{----- (3)}$$

The command stator flux and torque magnitudes are compared with the respective estimated values and the errors are processed through hysteresis band controller. The torque control of the inverter fed machine is carried out by hysteresis control of magnitude of stator flux and torque that selects one of the six active and two zero inverter voltage vectors as shown in Fig..2 [9]. The selection is made in order to maintain the torque and flux error inside the hysteresis band in which the errors are indicated by and respectively ΔT_e and $\Delta\psi_s$ respectively.

$$\Delta T_e = T_e^* - T_e \quad \text{----- (4)}$$

$$\Delta\psi_s = \psi_s^* - \psi_s \quad \text{----- (5)}$$

The six different directions of V_s are denoted as V_i ($i = 1, 2, 3 \dots 6$). Considering S_a, S_b and S_c as the combination of switches, the status of the inverter are given by (6) [10]

$$V_i = \frac{2V_s}{3} \left(S_a + e^{j\frac{2\pi}{3}} S_b + e^{j\frac{4\pi}{3}} S_c \right) \quad \text{----- (6)}$$

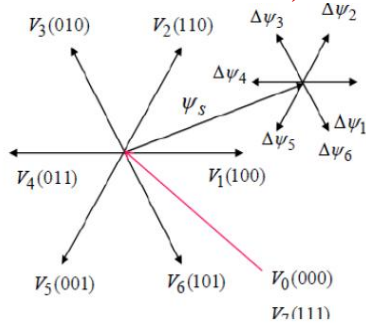


Fig. 2 Inverter voltage vectors and corresponding stator flux for six sectors

The flux loop controller has two levels of digital output according to the following relations

$$\begin{aligned}
 H_{\psi} &= 1 \text{ for } E_{\psi} > +HB_{\psi} \\
 H_{\psi} &= -1 \text{ for } E_{\psi} < -HB_{\psi}
 \end{aligned}
 \tag{7}$$

The total hysteresis band width of the flux loop controller is $2H_{\psi}$. The actual stator flux is constrained within this band and it tracks the command flux in zigzag path as shown in Fig. 3. The torque control loop has three levels of digital output, which possess the following relation

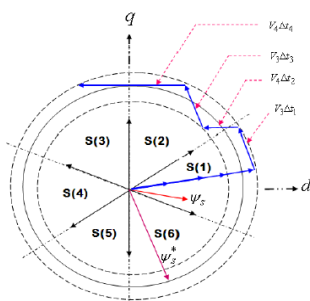


Fig. 3 Trajectory of stator flux vectors

$$\begin{aligned}
 H_{T_e} &= 1 \text{ for } E_{T_e} > +HB_{T_e} \\
 H_{T_e} &= 0 \text{ for } -HB_{T_e} < E_{T_e} < +HB_{T_e} \\
 H_{T_e} &= -1 \text{ for } E_{T_e} < -HB_{T_e}
 \end{aligned}
 \tag{8}$$

The feedback flux and torque are calculated from the machine terminal voltages and currents. The signal computation block computes the sector number in which the flux vector currently lies. There are six active voltage vectors each spanning 60° . The voltage vector table receives H_{ψ} , H_{T_e} , and $S(i)$ sector and generates the appropriate control for the inverter from a look-up table.

III. FLUX and TORQUE ESTIMATOR

Flux and torque estimators are used to determine the actual value of torque and flux linkages. Into this block enters the VSI voltage vector transformed to the $d-q$ stationary reference

frame. The three-phase variables are transformed into the $d-q$ axes variables using the following transformation.

$$\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The $d-q$ axes stator flux linkage is estimated by computing the integral of difference between the respective $d-q$ input voltage and the voltage drop across the stator resistance

$$\begin{aligned}
 \psi_{ds} &= \int (v_d - i_{ds} r_s) dt \\
 \psi_{qs} &= \int (v_q - i_{qs} r_s) dt
 \end{aligned}
 \tag{9}$$

The resultant stator flux linkage can be expressed as

$$\psi = \sqrt{\psi_{ds}^2 + \psi_{qs}^2}
 \tag{10}$$

The location of the stator flux linkage should be known so that the appropriate voltage vector is selected depending upon the flux location.

$$\theta_e = \tan^{-1} \left(\frac{\psi_{qs}}{\psi_{ds}} \right)
 \tag{11}$$

The electromagnetic torque can be expressed as

$$T_e = \left(\frac{3}{2} \right) \left(\frac{P}{2} \right) (\psi_{ds} i_{qs} - \psi_{qs} i_{ds})
 \tag{12}$$

Eqns (9)-(12) pertain to the flux and the torque estimator. The model of Flux and Torque estimator in SIMULINK is as shown Fig.4. The flux and torque are estimated by using the current and voltage measurement of IM drive. By using the model in the figure the torque, flux and flux angle are derived which are used for torque and flux hysteresis.

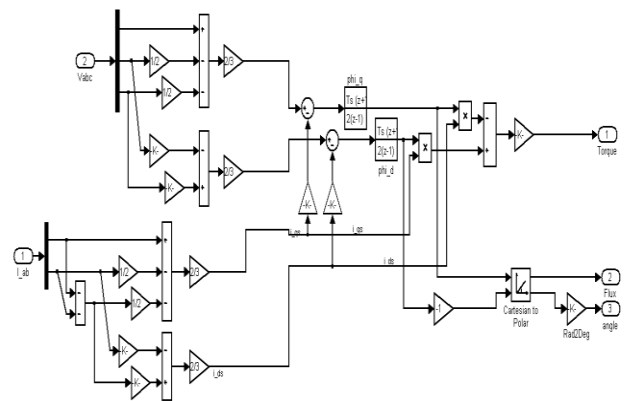


Fig 4. SIMULINK model of flux and the torque estimator

The sector division for 12 sectors DTC is as shown in Fig. 5. As indicated in the figure all the six vectors are used in all the sectors thus reducing the torque ambiguity which occurs in case of six sectors DTC. Here FD indicates flux decrease and FI represents flux increase. TD represents torque decrease, TI represents torque increase, TsI represents small increase in torque and TsD represents small decrease in torque. Thus twelve sectors DTC consist of two level flux hysteresis and four level torque hysteresis for reducing the repulsion in torque and flux.

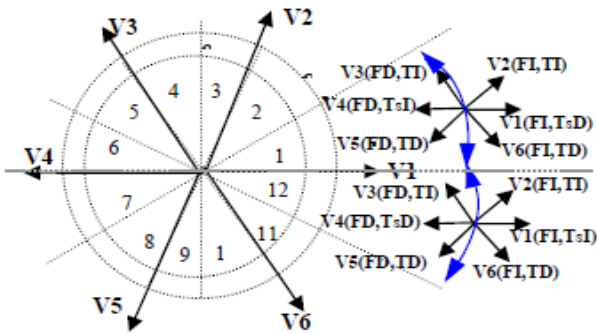


Fig 5 Sector division for twelve sectors DTC

In 12 sectors DTC, it is necessary to define small and large variations. It is obvious that V1 will produce a large increase in flux and a small increase in torque in sector S12. On the contrary, V2 will increase the torque in large proportion and the flux in a small one. It is reasonable to deduce that the torque error should be divided in the number of intervals. Therefore, the hysteresis block should have four hysteresis levels. The value for flux increase is 1 and decrease is 0 is considered. The torque hysteresis is considered as 1, 2,-2,-1. The switching table for 12 sectors DTC for four level torque hysteresis is as shown below in table I[11].

Table I: Switching table for the 12_DTC.

Φ	τ	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇	S ₈	S ₉	S ₁₀	S ₁₁	S ₁₂
FI	TI	V ₂	V ₃	V ₃	V ₄	V ₄	V ₅	V ₅	V ₆	V ₆	V ₁	V ₁	V ₂
	TsI	*V ₂	V ₂	*V ₃	V ₃	*V ₄	V ₄	*V ₅	V ₅	*V ₆	V ₆	*V ₁	V ₁
	TsD	V ₁	*V ₁	V ₂	*V ₂	V ₃	*V ₃	V ₄	*V ₄	V ₅	*V ₅	V ₆	*V ₆
	TD	V ₆	V ₁	V ₁	V ₂	V ₂	V ₃	V ₃	V ₄	V ₄	V ₅	V ₅	V ₆
FD	TI	V ₃	V ₄	V ₄	V ₅	V ₅	V ₆	V ₆	V ₁	V ₁	V ₂	V ₂	V ₃
	TsI	V ₄	*V ₄	V ₅	*V ₅	V ₆	*V ₆	V ₁	*V ₁	V ₂	*V ₂	V ₃	*V ₃
	TsD	V ₇	V ₅	V ₀	V ₆	V ₇	V ₁	V ₀	V ₂	V ₇	V ₃	V ₀	V ₄
	TD	V ₅	V ₆	V ₆	V ₁	V ₁	V ₂	V ₂	V ₃	V ₃	V ₄	V ₄	V ₅

IV. Simulation Results

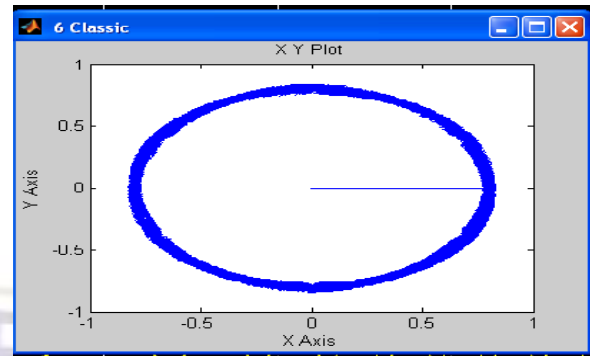


Fig .6 Simulation results of stator flux locus of C-DTC

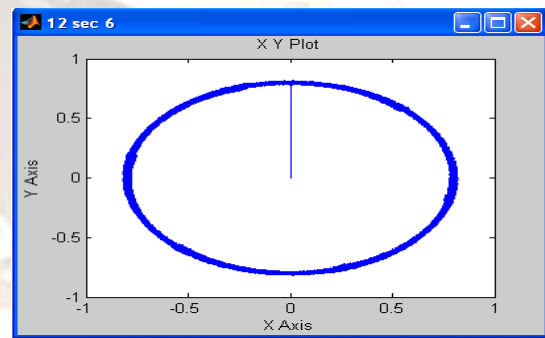


Fig .7 Simulation results of stator flux locus of 12sector-DTC

Fig.6 and Fig.7 represents the stator flux locus of conventional DTC and twelve sectors DTC respectively. By comparing the results of flux locus of C_DTC and 12_DTC, we can observe that the flux repulsion has been reduced in 12_DTC compared with C_DTC. In order to check theoretically, the percentage flux repulsion is determined in both the methods of DTC. The load is applied to IM after 0.5s the machine is started. Hence at time t=0.2 seconds (before applying load), the flux repulsion in C_DTC is 14.81% and flux repulsion in 12_DTC is 6.97%. At time 0.7 seconds (after applying load) the flux repulsion in C_DTC is 16.82% and flux repulsion in 12_DTC is 7.32%. Since the percentage flux repulsion in C_DTC is more compared with that of 12_DTC before and after applying load, it can be theoretically also tested that the flux repulsion in 12_DTC is less than that of C_DTC.

Fig.8 and Fig.9 represent the torque v/s time characteristics of C_DTC and 12_DTC respectively. From both the results we can observe that, the torque repulsion is less in 12_DTC as that of C_DTC. For theoretical verification of the result obtained, the percentage torque repulsion is calculated. The percentage is calculated before

applying load and after applying load. The percentage torque repulsion of C_DTC at time $t=0.2s$ is 61.36% and 12_DTC is 26.47% before applying load and at time $t=0.7s$ is 31.18% in C_DTC and 11.90% in 12_DTC after applying load. Hence by comparing the percentage repulsion in both the cases, we can state that torque repulsion is reduced in 12_DTC compared with C_DTC.

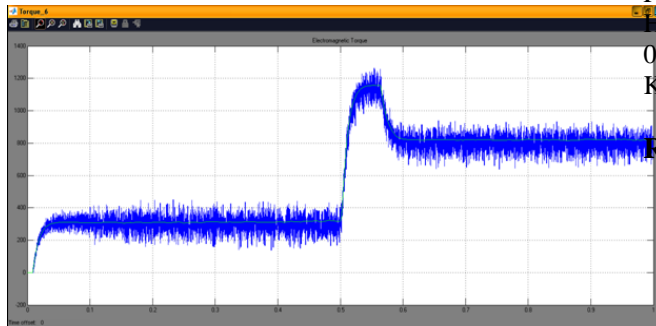


Fig.8 Simulation Result for torque v/s time for C_DTC.

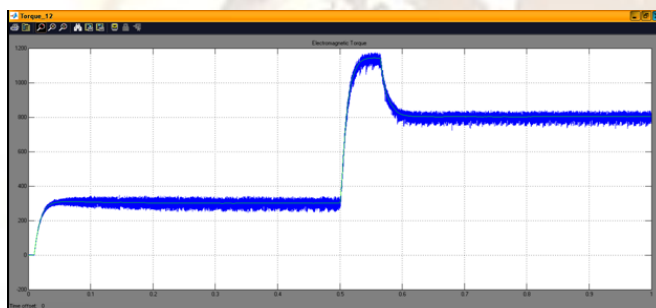


Fig.9 Simulation Result for torque v/s time for 12_DTC .

V. Conclusion

This paper presents a direct torque control of Induction machine with six sectors and twelve sectors for use in various applications to reduce the repulsion in torque and flux. The circuit structure is simple, good performance and robustness. Conventional DTC gives fast torque response and better control over torque and flux. However the main drawback of this method comes from the fact that the voltage vector is applied continuously over a sample time. As a result if the torque error is small the torque developed after one cycle may not only reach the desired level but also overshoot. This leads to increased ripples in the torque developed.

Accordingly the twelve sectors DTC of IM Drive is applicable to reduce the torque and flux repulsion. In this paper, a method is presented to reduce the torque and flux fluctuation by increasing the number of sector in conventional DTC. Here it is

observed that by increasing the number of sector from six to twelve and changing the switching table has reduced the torque and flux repulsion compared with six sectors DTC.

APPENDIX

The parameters of the three-phase Induction motor, employed for simulation purpose, in SI units are $P_n=149.2e3$, Voltage (L-L)= 460V ,frequency = 60 Hz , $R_r=9.295e-3$, $R_s=14.85e-3$, $L_s'=0.3027e-3$, $L_r=0.3027e-3$, $L_m=10.46e-3$, $p=2$, inertia=3.1 Kg m^2 , $T_r=L_r/R_r$.

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