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Control of Induction Motor Drive Using Direct Torque Control with 12 Sectors

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Abstract: *The advantage of Direct Torque Control (DTC) of inverter-fed Induction Machine is high dynamic performance by means of very simple control structure. Using DTC technique, we can eliminate complexity of Field Oriented Control (FOC); but it doesn't drive the Induction Machine as well as FOC. Recent researches have introduced improvements in DTC. In this paper we present a new DTC method with 12 sectors, in spite of 6 sectors in classical DTC, which make it more optimal.*

Keywords: Induction Motor; DTC; FOC; Sector; Torque; Flux

1. Introduction

In order to find optimal and economical methods of driving structures of electrical machine, scalar control methods have been abandoned and Field Oriented Control (FOC) of machine have been developed. The prominence of FOC techniques to the one of scalar is changing calculation of induction motor to the DC motor in the view of control system. But despite of all benefits of FOC, the complexity and needs of powerful processors have made it less widespread.

In DTC techniques, the drawback of FOC, the intricacy, is eliminated and induction motor drives become simpler. But the result is increase of torque and flux ripple. However these problems can be ignored because of high simplicity.

Recently some investigations have been done to improve DTC [3]. In the following sections, we will introduce an optimal improvement in classical DTC; then it would be simulated in MATLAB/SIMULINK to observe the result of an induction motor.

2. Principles of Direct Torque Control

The electromagnetic torque in a three-phase induction machines can be expressed as follows:

$$T_e = \frac{2}{3} P \psi_s \times i_s \qquad (2.1)$$

Where Ψ_s is the stator flux, i_s is the stator current (both fixed to the stationary reference frame fixed to the stator) and P is the number of pairs of poles. The previous equation can be modified and expressed as follows:

$$T_e = \frac{3}{2} P |\psi_s| \cdot |i_s| \cdot \sin(\alpha_s - \rho_s) \qquad (2.2)$$

Where ρ_s is the stator flux angle and α_s is the stator current one, both referred to the horizontal axis of the stationary frame fixed to the stator.

If the stator flux modulus is kept constant and the angle ρ_s is changed quickly, then the electromagnetic torque is directly controlled.

The same conclusion can be obtained using another expression for the electromagnetic torque:

$$T_e = \frac{3}{2} P \frac{l_m}{L_s L_r - L_m^2} |\psi'_r| \cdot |\psi_s| \cdot \sin(\rho_s - \rho_r) \qquad (2.3)$$

Because of the rotor time constant is larger than the stator one, the rotor flux changes slowly compared to the stator flux; in fact, the rotor flux can be assumed constant. As long as the stator flux modulus is kept constant, then the electromagnetic torque can be rapidly changed and controlled by means of changing the angle $\rho_s - \rho_r$.

3. DTC Controller

The way to impose the required stator flux is by means of choosing the most suitable Voltage Source Inverter state. If the ohmic drops are neglected for simplicity, then the stator voltage impresses directly the stator flux in accordance with the following equation:

$$\frac{d\psi_s}{dt} = v_s \qquad (3.1)$$

Or:

$$\Delta\psi_s = v_s \Delta t \qquad (3.2)$$

Decoupled control of the stator flux modulus and torque is achieved by acting on the radial and tangential components respectively of the stator flux-linkage space vector in its locus. These two components are directly proportional (Rs=0) to the components of the same voltage space vector in the same directions.

3.1 Classical DTC with 6 Sectors

Figure 1 shows the possible dynamic locus of the stator flux, and its different variation depending on the VSI states chosen. In classical DTC, the possible global locus is divided into six different sectors.

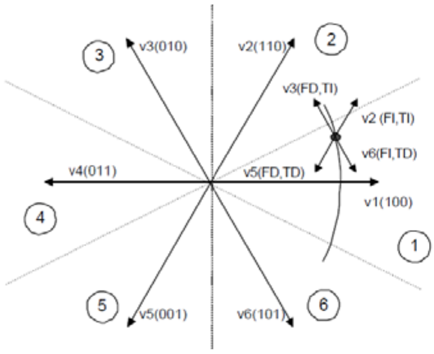

Fig 1: Stator flux vector locus and different possible switching voltage vectors. FD: flux decrease. FI: flux increase. TD: torque decrease. TI: torque increase.

In Accordance with figure 1, the general able 1 can be written. It can be seen from table 1, that the states V_k and V_{k+3} , are not considered in the torque because they can both increase (first 30 degrees) or decrease (second 30 degrees) the torque at the same sector depending on the stator flux position. The usage of these states for controlling the torque is considered one of the aims to develop in the present paper, dividing the total locus into twelve sectors instead of just six.

TABLE I: General Selection Table for Direct Torque Control, being "k" the sector number.

Voltage Vector	Increase	Decrease
Stator Flux	V_k,V_{k+1},V_{k-1}	V_{k+2},V_{k-2}, V_{k+3}
Torque	V_{k+1}, V_{k+2}	V_{k-1}, V_{k-2}

Finally, the DTC classical look up table is as follows:

TABLE II: Look up table for Direct Torque Control.

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
FI	TI	V_2	V_3	V_4	V_5	V_6	V_1
	T=	V_0	V_7	V_0	V_7	V_0	V_7
	TD	V_6	V_1	V_2	V_3	V_4	V_5
FD	TI	V_3	V_4	V_5	V_6	V_1	V_2
	T=	V_7	V_0	V_7	V_0	V_7	V_0
	TD	V_5	V_6	V_1	V_2	V_3	V_4

FD/FI: flux decrease/increase. TD/=/I: torque decrease/equal/increase. S_x: stator flux sector. Φ: stator flux modulus error after the hysteresis block. τ: torque error after the hysteresis block.

The sectors of the stator flux space vector are denoted from S_1 to S_6. Stator flux modulus error after the hysteresis block (Φ) can take just two values. Torque error after the hysteresis block (τ) can take three different values. The zero voltage vectors V_0 and V_7 are selected when the torque error is within the given hysteresis limits, and must remain unchanged.

4. Improvement in DTC By 12-Sector Table

In classical DTC there are two states per sector that present a torque ambiguity. Therefore, they are never used. It seems a good idea that if the stator flux locus is divided into twelve sectors instead of just six, all six active states will be used per sector. This new stator flux locus is introduced in figure 2. Notice how all six voltage vectors can be used in all twelve sectors. However, it has to be introduced the idea of small torque increase instead of torque increase, mainly due to the fact that the tangential voltage vector component is very small and consequently its torque variation will be small as well.

Table 3 can be written when a twelve-sector locus is used.

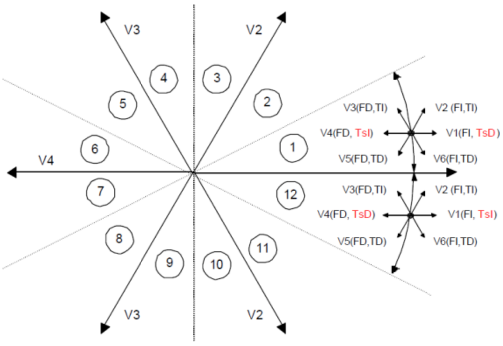

Fig 2: Twelve sector modified DTC (12_DTC) and its sectors. FD/FI: flux decrease/increase. TD/TI: torque decrease/increase. TsD/TsI: torque small decrease/increase. Notice how all six voltage vectors can be used in all twelve sectors, disappearing all ambiguities.

TABLE III: Table for sectors 12 and 1 in the 12_DTC. Notice how all six voltage vectors can be used in all sectors disappearing all ambiguities.

S_{12}	Increase	Decrease
Stator Flux	V_1,V_2, V_6	V_3,V_4,V_5
Torque	V_1,V_2,V_3	V_4,V_5,V_6
S_1	Increase	Decrease
Stator Flux	V_1,V_2, V_6	V_3,V_4,V_5
Torque	V_2,V_3,V_4	V_5,V_6,V_1

As it has been mentioned in the previous paragraph, it is necessary to define small and large variations. It is obvious that V_1 will produce a large increase in flux and a small increase in torque in sector S_{12}. On the contrary, V_2 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 that later on will be measured. Therefore, the hysteresis block should have four hysteresis levels at is suggested in table 4.

Finally, the look up table is presented in table 4.

TABLE IV: 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

FD/FI: flux decrease/increase. TD/=/I: torque decrease/equal/increase. S_x: stator flux sector. Φ: stator flux modulus error after the hysteresis block. τ: torque error after the hysteresis block.
(* there is no suitable state. It has been chosen the second most suitable).

5. DTC Schematic

In figure 3 a possible schematic of Direct Torque Control is shown. As it can be seen, there are two different loops corresponding to the magnitudes of the stator flux and torque. The reference values for the flux stator modulus and the torque are compared with the actual values, and the resulting error values are fed into the hysteresis blocks. The outputs of the stator flux error and torque error hysteresis blocks, together with the position of the stator flux are used as inputs of the look up table (see table 2 and 4). The position of the stator flux is divided into six different sectors. In accordance with the figure 3, the stator flux modulus and torque errors tend to be restricted within its respective hysteresis bands.

The DTC requires the flux and torque estimations, which can be performed as it is proposed in figure 3 schematic, by means of two different phase currents and the state of the inverter.

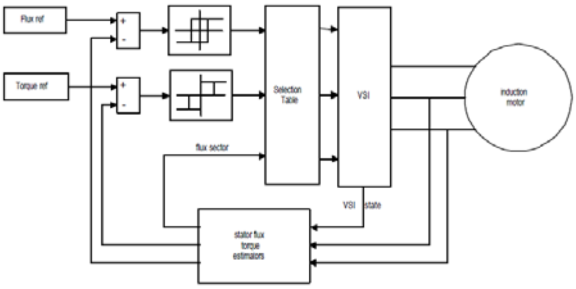

Fig 3: Direct Torque Control schematic

6. Simulation And Results

To simulate a DTC controller of induction motor in MATLAB/SIMULINK, it’s better to use discrete integrators instead of continues; because it increase processing and simulation speed by selecting time step of 2e-6 seconds and so we would have better results.

The parameters of induction motor are shown in table 5.

TABLE V: Parameters of induction motor

P_n(VA)	149.2e3	R_s(Ω)	14.85e-3	L'_{lr}(H)	0.303e-3
$V_{n,ll}$(V)	460	L_{ls}(H)	0.303e-3	L_m(H)	10.46e-3
F_n(Hz)	60	R'_r(Ω)	9.295e-3	J(Kg.m^2)	3.1

Here we want to change the switching table of SVM inverter to improve its performance by increasing DTC sectors to twelve; so that all vectors would be used during process of torque control. So in this simulation model, we have used 2D look-up tables of SIMULINK, which are set according to table 4.

By means of calculating flux angle, 12 sectors can be modified and also by modifying eight voltage vectors, the inverter would be signalled on the basis of what we described in previous sections.

The output of simulation is illustrated in figures 4-8. As we can see, the electromagnetic torque and rotor speed follow the reference values very well, except at the moment that the rotor speed is going to change, that we can see noticeable error. Also the torque and stator flux ripple, as we had mentioned before, is obvious.

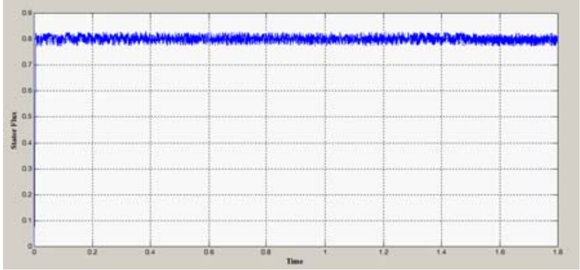

Fig. 4: stator flux

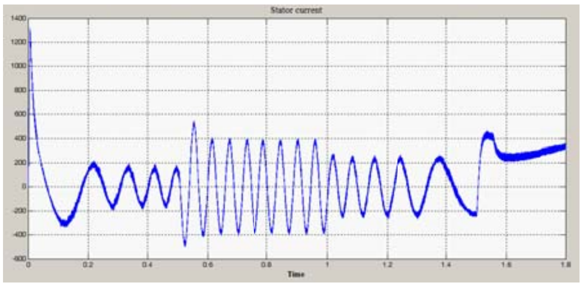

Fig 5: stator current

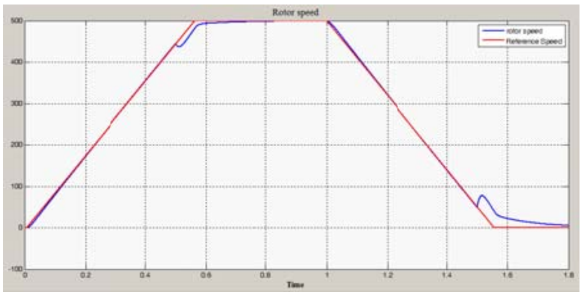

Fig. 6: rotor speed follows the reference value

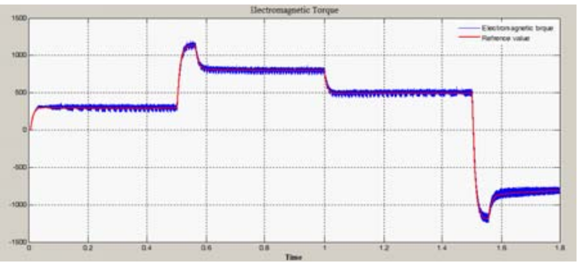

Fig. 7: electromagnetic torque follows the reference value

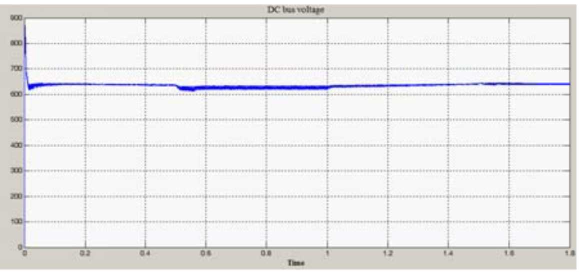

Fig. 8: DC bus voltage

7. Conclusion

Direct Torque Control (DTC) method that is a very optimal and economical technique in motor drive planning needs improvements so that its advantages would be eliminated.

So a new strategy in DTC is introduced and presented in this paper. In classical DTC there are two states per sector that present a torque ambiguity. Therefore, they are never used. It seems a good idea that if the stator flux locus is divided into twelve sectors instead of just six, all six active states will be used per sector.

The simulation of this method also shows desired results that we expected to see; the rotor speed and electromagnetic torque follows the reference values very well.

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