VOLTAGE SWITCHING TABLES FOR DIRECT TORQUE CONTROL OF PMSM DRIVE

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Controlul direct în cuplu (DTC) este una dintre metodele de comandă care se bazează pe controlul în flux şi în cuplu. Dintre toate metodele de comandă a cuplului motorului sincron cu magnet permanent (PMSM), DTC ese cea care asigură un răspuns rapid şi robust al cuplului fără a folosi senzori de poziţie sau de viteză, transformarea de coordonate, generarea de pulsuri PWM şi regulatoare de curent. Aceasta abordare propune o schemă de control în care cuplul electromagnetic şi valoarea fluxului rotoric sunt estimate numai cu ajutorul tensiunilor şi curenţilor. Estimarea nu depinde de parametrii motorului cu excepţia rezistenţei electrice a înfăşurării statorice.

Articolul prezintă cercetările autorilor privind efectul vectorilor spaţiali de tensiune zero în sistemele DTC ale PMSM şi arată că, folosind raţional tensiunile zero, sistemele DTC pot fi comandate cu succes, iar variaţia cuplului este redusă semnificativ şi performanţa sistemului este îmbunătăţită. Eficienţa strategiei este analizată prin modelarea implementării şi folosirea unor tabele de comutaţie specifice pentru PMSM interior.

The direct torque control(DTC) is one of the actively researched control which is based on decoupled control of flux and torque. Among all methods of torque control of permanent magnet synchronous motor (PMSM), DTC achieves robust and fast torque response without the need of speed or position sensors, coordinate transformation, PWM pulse generation and current regulators. In fact, this approach proposes a control scheme where the electromagnetic torque and stator flux magnitude are estimated with only stator voltages and currents. The estimation does not depend on motor parameters except for the stator resistance.

The paper describes an investigation about the effect of the zero voltage space vectors in the DTC system of PMSM and shows that if using the zero voltages rationally, not only the DTC system can be driven successfully but torque ripple is significantly reduced and performance of the system is improved. The effectiveness of the strategy is analysed by modelling implementation and switching tables specifics for an interior PMSM are derived.

Keywords: DTC, PMSM, Switching tables, Stator flux linkage

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1. Introduction

Research interest in PMSM drives has grown significantly over the past few years due to some of their advantages such as, high power density, high torque to inertia ratio, free maintenance and high efficiency. Actually, efforts are devoted to develop robust control strategies and tried to reduce the torque ripple and to fix the switching frequency of the inverter. The DTC is a typical example of these applications. Many PMSM are used in applications that require a quick and robust torque response. To simplify torque control, it is assumed that output torque is proportional to applied current. This assumption may not always be correct, due to non-uniformity of magnetic materials, current sensors non-linearities and current controller limitations. Theses factors can lead to high values of torque ripple and copper loss [1][2].

In the indirect torque control scheme, currents are regulated by using PWM or hysteresis controllers, which operate in the rotor reference frame. Before switching the inverter, the modified current errors are transformed to the stator by a dq^{-1} transformation using measured rotor position from an encoder. Current controllers followed by hysteresis or PWM comparators are not used in DTC systems [3][4].

DTC, first proposed for induction motors, can be applied to all AC machine drives. In addition it seems to become an alternative for the classic variable speed AC drives. The basic idea of DTC is to choose the best voltage vector, which makes the flux rotate and produce the desired torque. During this rotation, the amplitude of the flux rests in a predefined band. Thus it is almost constant. The torque is estimated using measured currents and estimated fluxes. Switching commands of inverter come directly from a look up table. This one not only simplifies the control system but also decreases its processing time [5].

There have been some DTC based strategies, e.g., voltage vector selection strategy using a switching table, direct self control and space vector modulation. Among them, the first strategy using switching tables is widely researched and commercialized, because it is very simple in concept and very easy to be implemented without complicated over-modulation technique. The control block diagram of the proposed method is shown in Fig. 1. The DTC is increasingly drawing interest because of,

- Simplicity of its structure.
- Elimination of the current controllers.
- Inherent delays.
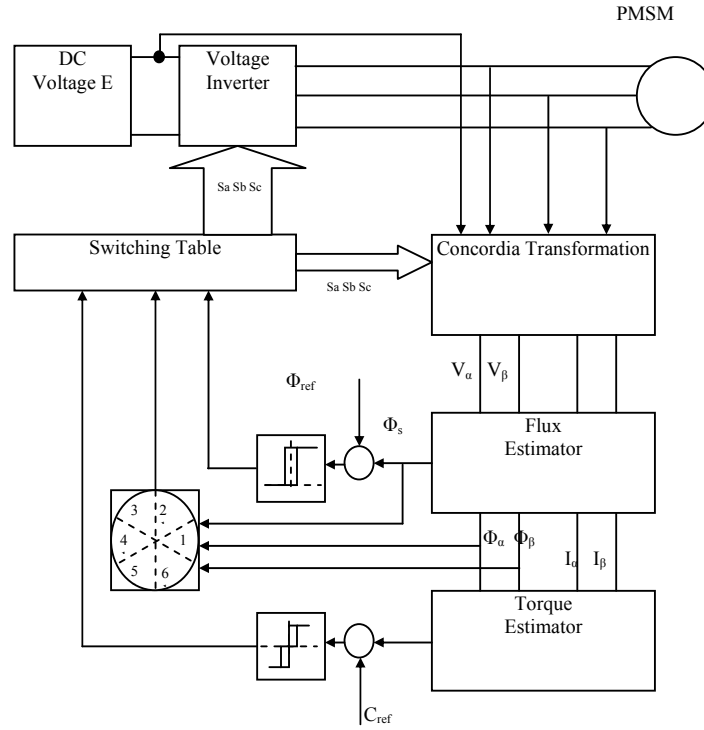- Elimination of rotor position sensor.

Fig. 1. DTC block diagram of PMSM

2. Machine equations

The motor considered in this paper is an interior PMSM which consists of a three phase stator winding and a PM rotor. The voltage equations in a synchronous reference frame can be derived as follows [3][4],

$$V_d = R_s.I_d. + \frac{d\phi_d}{dt} - \omega.\phi_q \tag{1}$$

$$V_q = R_s.I_q. + \frac{d\phi_q}{dt} + \omega.\phi_d \tag{2}$$

Where the direct and quadrature axis flux linkages are,

$$\phi_d = L_d.I_d. + \phi_f \tag{3}$$

$$\phi_q = L_q.I_q \tag{4}$$

The torque is calculated with:

$$C = \frac{3}{2} n_p \cdot \left\{ \phi_f . I_q + (L_d - L_q) . I_d . I_q \right\}$$ (5)

The motor dynamics can be simply described by the equation (6).

$$\frac{J}{n_p} \frac{d\omega_r}{dt} + \frac{f}{n_p} . \omega_r = C_{em} - C_{st}$$ (6)

In equation (5), the first term represents the magnet torque due to the rotor PM flux ϕ_f. The second term is the reluctance torque component due to the complex interaction of d-q axis currents and inductances. For an interior PMSM L_q is larger than L_d, and the complexity of the control arises due to the non-linear nature of the torque equation. By using the concept of the field orientation, it can be assumed that the d-axis current is controlled to be zero. Thus, the PMSM has the best dynamic performance and also operates in the most efficient state. Under this assumption, the contribution of the second term of the electric torque equation becomes effectively negligible and the reduced dynamic model of the PMSM is given by the following equations [5][6].

$$\frac{dI_q}{dt} = \frac{1}{L_q} . V_q - \frac{R_s}{L_q} . I_q - \frac{\phi_f}{L_q} . \omega_r$$ (7)

$$\frac{J}{n_p} \frac{d\omega_r}{dt} = K_T . I_q - \frac{f}{n_p} . \omega_r - C_{st}$$ (8)

$$\frac{d\theta}{dt} = \omega_r$$ (9)

3. DTC Algorithm

The electromagnetic torque equation can be expressed in terms of the stator flux linkage and its angle with respect to the rotor flux linkage as follows :

$$C = 0.75 n_p \left[\frac{2.\phi_f . \phi_s}{L_d} . \sin(\delta) + \phi_s^2 . \left\{ \frac{1}{L_q} - \frac{1}{L_d} \right\} . \sin(2\delta) \right]$$ (10)

For a surface magnet motor, equation 10 becomes,

$$C = 1.5.n_p . \frac{\phi_f . \phi_s}{L} . \sin(\delta) \qquad (11)$$

The angle between the stator and rotor flux linkages, noted δ, is the load angle when the stator resistance is neglected. In the steady state, the load angle is constant corresponding to a load torque. Both the stator and rotor fluxes rotate at the synchronous speed. In transient state, the load angle varies and the flux vectors rotate at different speeds. The relationship between torque C and δ may be linear in some cases, and may not be linear in others cases as depicted by Fig. 2.

Fig. 2 shows the torque-load angle characteristics of PMSM drive. When the flux amplitude is at $0.5\phi_f$, $0.75\phi_f$, ϕ_f, $1.5\phi_f$, $2\phi_f$ and $3\phi_f$. For the two last cases, the derivative of torque near zero crossing is negative. Then, the DTC can not be applied. The condition for positive derivative of the torque with respect to the load angle is given by equation (12).

For obtaining fast dynamic torque response, the amplitude of stator flux linkage should be choosen according to relation (12). Otherwise, it should be varied with the change of actual torque if the linearity is more important. It should also be kept in mind that for the same torque a higher stator current is needed when the stator flux amplitude is lower [7][8].

$$\phi_s < \frac{L_q}{L_q - L_d} . \phi_f \qquad (12)$$

As seen from equation (10), torque is proportional to the angle δ, which must be changed quickly when fast dynamic response is required. At low speed, the ability to change δ and hence torque, is mainly determined by the motion of the rotor if zero voltage vectors V_7 and V_8 are selected. A quick variation of δ can be forced by applying voltage vectors which move quickly the stator flux linkage relative to rotor flux linkage. At high speed, the rotor may move sufficiently quickly to produce the required change in the angle δ and hence the torque. There are six non-zero voltage vectors V_1-V_6 and two zero voltage vectors V_7-V_0.
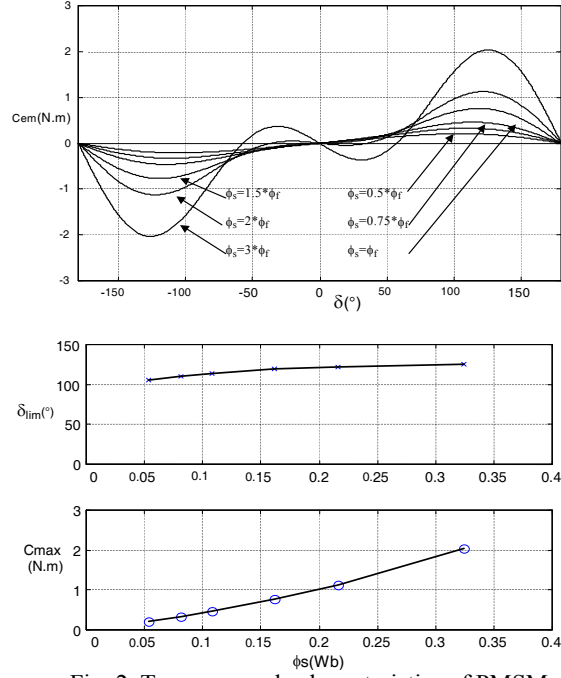
Fig. 2. Torque – angle characteristics of PMSM

The two zero voltage vectors are at the origin and the six non-zero voltage vectors are 60° apart from each other in voltage vector plane as shown by Fig. 3.
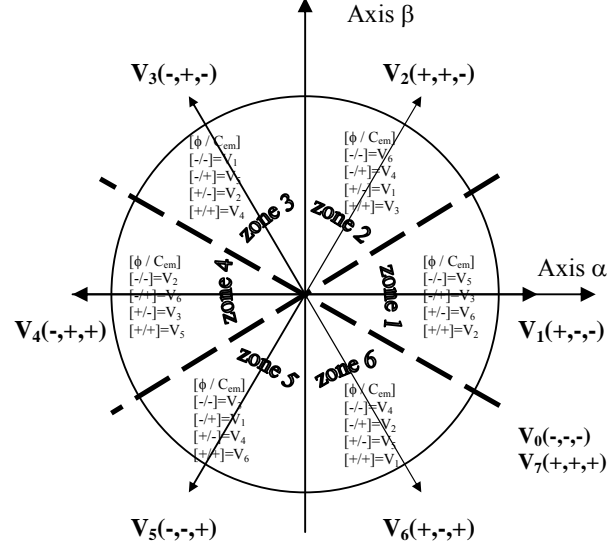

Fig. 3. Sectors and voltage vectors

During the switching intervals, each applied voltage vector remains constant and the stator fluxes are given in the stationary reference frame as,

$$\phi_\alpha(k+1) = \phi_\alpha(k) + h\left[V_\alpha(k) - R_s.I_\alpha(k)\right] \qquad (13)$$

$$\phi_\beta(k+1) = \phi_\beta(k) + h\left[V_\beta(k) - R_s.I_\beta(k)\right] \qquad (14)$$

Neglecting the stator resistance, equations 13 and 14 implies that the tip of the stator vector will move in the direction of the applied voltage vector in a straight line as indicated in Fig. 4. For controlling the amplitude of the stator flux, the voltage vector plane is divided into six regions. Each of this region is 60° wide. In each region, two adjacent voltage vectors may be selected to increase or decrease the stator flux amplitude and give a minimum switching frequency [9].
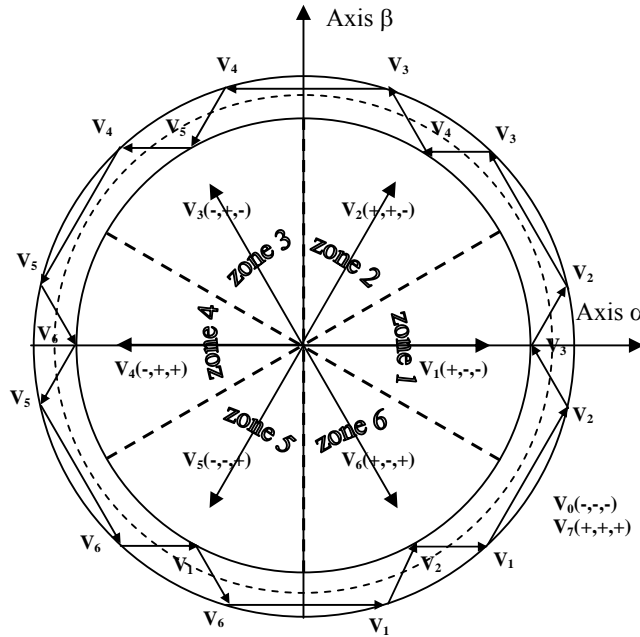

Fig. 4. Control of stator flux linkage with selected stator voltage vectors

In Fig. 4, the space between the two circles represents the hysteresis band in stator flux linkage amplitude which in turn is equal to the rated flux when operation below the based speed is called for. For field weakening, these two circles contract inward [10].

Fig. 5 shows the control structure for selecting the voltage vectors and keeping torque and flux linkage within pre-selected hysteresis bands [11][12].
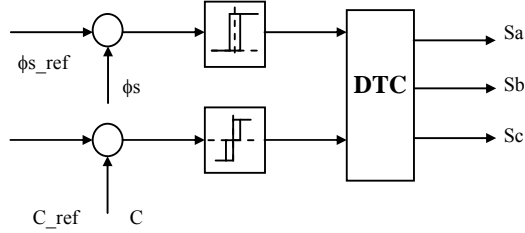

Fig. 5. Torque and flux hysteresis controllers for DTC of PMSM

4. Voltage switching tables for DTC

The torque and flux hysteresis controllers select the appropriate voltage vectors. Tables 1 and 2 indicate the six and eight voltage vectors switching strategies, in each region C and ϕ are increasing or decreasing functions of time. From Table 2, it is clear that when the torque is increasing or decreasing, the flux linkage can be increased or decreased by selecting alternatively one of the six non zero voltage vectors and one of the two zero voltage vectors [13][14]. From Table 1, the torque and flux are increased or decreased by selecting only the six non zero voltage vectors. The torque is changed by reversing the movement of the stator flux vector at each state of the hysteresis controller output [15].

Table 1

The six voltage vectors switching table

		Zone =1	Zone =2	Zone =3	Zone =4	Zone =5	Zone =6
R_ϕ=1 (ϕ↑)	R_c=1 (C↑)	V_2(1,1,–1)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)
	R_c=0 (C↓)	V_6(1,-1,1)	V_1(1,-1,-1)	V_2(1,1,–1)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)
R_ϕ=0 (ϕ↓)	R_c=1 (C↑)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)	V_2(1,1,–1)
	R_c=0 (C↓)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)	V_2(1,1,–1)	V_3(-1,1,-1)	V_4(-1,1,1)

Table 2
The eight classic voltage vectors switching table

		Zone =1	Zone =2	Zone =3	Zone =4	Zone =5	Zone =6
R_ϕ=1	R_c=1 (C↑)	V_2(1,1,–1)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)
(φ↑)	R_c=0 (C↓)	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)
R_ϕ=0	R_c=1 (C↑)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)	V_2(1,1,–1)
(φ↓)	R_c=0 (C↓)	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)

The use of the six voltage vectors switching table implies that the stator flux linkage is always kept in motion, making it to go forward and backward in order to regulate the torque loop. For controlling the amplitude of stator flux and therefore for changing the torque, zero voltage vectors V_7 and V_8 are not used in PMSM drives. In Tables 1 and 2, R_ϕ and R_C are the outputs of the hysteresis controllers. Zone=1,…6 represent the regions numbers for the stator flux linkage positions.

Table 3
Switching table with three-level torque controller

		Zone=1	Zone=2	Zone=3	Zone=4	Zone=5	Zone=6
R_ϕ=1	R_c=1 (C↑)	V_2(1,1,–1)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)
(φ↑)	R_c=0	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)
	R_c=-1 (C↓)	V_6(1,-1,1)	V_1(1,-1,-1)	V_2(1,1,–1)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)
R_ϕ=0	R_c=1 (C↑)	V_3(-1,1,-1)	V_4(-1,1,1)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)	V_2(1,1,–1)
(φ↓)	R_c=0	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)	V_0(-1,-1,-1)	V_7(1,1,1)
	R_c=-1 (C↓)	V_5(-1,-1,1)	V_6(1,-1,1)	V_1(1,-1,-1)	V_2(1,1,–1)	V_3(-1,1,-1)	V_4(-1,1,1)

Rule A : If φs > φref+Δφ then R_ϕ=1,
　　　If φs < φref-Δφ then R_ϕ=0,
　　　else no change
Rule B : For ΔC>0, If C > Cref+ΔC then R_C=1,
　　　If   ecpl(k)> ecpl(k-1) then R_C=0,
　　　else R_C=1,
Rule C : For ΔC<0, If C < Cref-ΔC then R_C=-1,
　　　else if ecpl(k)< ecpl(k-1) then R_C=0,
　　　else R_C=-1,

5. Simulation results.

To study the performance of the DTC control, the simulation of the system was conducted using Matlab programming environment. Fig. 6 shows that the motor can follow the command torque very well. However, relatively high torque

ripples are observed. The estimated stator flux has the same form of the flux reference and Fig. 6 shows how the voltage vectors are selected for keeping ϕ_s within hysteresis band when ϕ_s is rotating in the counter clockwise direction.

The PMSM was simulated under the DTC drive system at high and low speed. Fig. 7 revealed loss of control over torque and stator flux when the zero voltage algorithm is used. It is seen however that the ripples in torque and flux characteristics are considerably lower when the eight voltage vectors in Table 2 are used. This implies that Table 2 is more appropriate for high speeds operations.

As mentioned from equation (10), the torque is proportional to the angle δ, which must be changed quickly. Unlike the asynchronous motor where change of slip frequency brought about by applying zero voltage vectors, the angle δ in the case of PMSM is determined also by the position of the rotor flux linkage which is non zero at all times. To control torque at low speed, quick change of δ can be obtained by avoiding the zero voltage vectors and by applying vectors which move the stator flux relative to rotor flux as quickly as possible. At high speed, this may not be necessary where the rotor move sufficiently to produce the required change in torque. The conventional eight voltage vector switching table is normally used in the DTC of induction motors and does not seem to regulate the torque and stator flux in PMSM drive well when the motor operates at low speed.
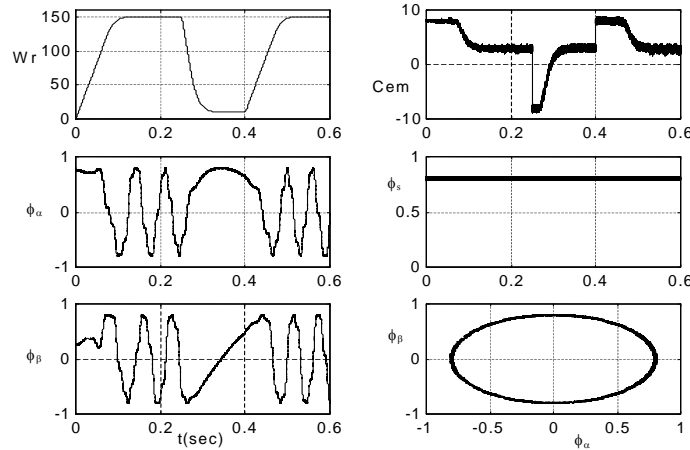
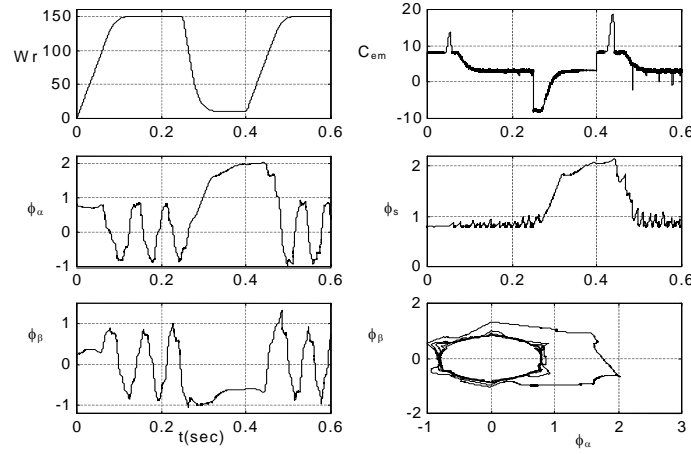Fig. 6. DTC without zero voltage vectors.
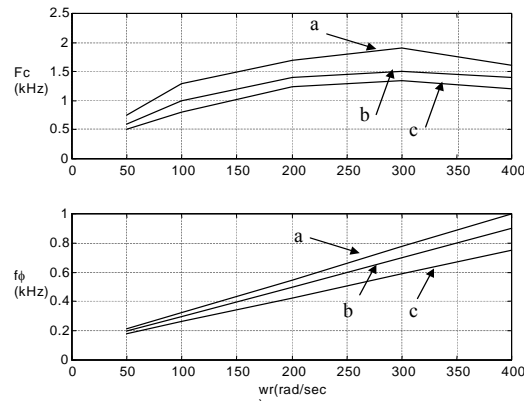
Fig. 7. DTC with zero voltage vectors

Fig. 8. Switching frequencies of torque and flux versus speed.
a)$\Delta C= \Delta\phi=0.01$ b) $\Delta C= \Delta\phi=0.025$ c) $\Delta C= \Delta\phi=0.1$

To overcome the previously mentioned difficulties, an algorithm is proposed in Table 3, which consists in combination of advantages of the two classic tables simultaneously and has advantage of conceptual simplicity. Modelling results for similar operating conditions with three levels torque hysteresis controller are presented in Fig. 9.
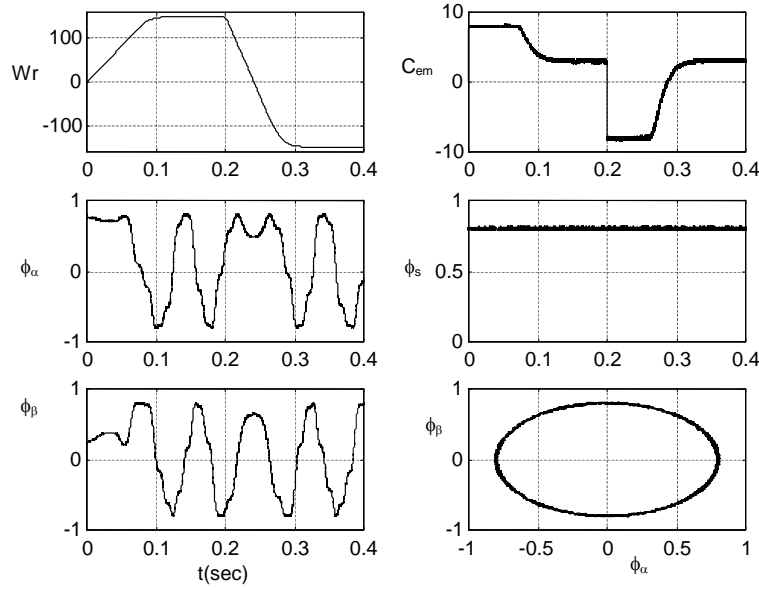
Fig. 9. DTC with three level torque controller.

The hysteresis band has to be set large enough to limit the inverter switching frequency below a certain level. The amplitude of the hysteresis band strongly influences the inverter performance such as torque and flux ripples, current harmonics and switching frequency.

The switching frequency variation characteristic of the flux hysteresis controller is different from that of torque hysteresis controller. As shown in Fig. 8, the switching frequency has a maximum value in a medium speed range. For the flux controller, the switching frequency is proportional to the motor speed.

This phenomenon makes flux and torque hysteresis controllers to have different contributions to the total switching frequency. It means that the amplitude of flux and torque hysteresis controllers should be regulated separately for effective utilisation of given total switching frequency controller command.

6. Conclusions

The paper has presented a DTC control with combination of both the six and eight voltage vectors tables, which does not require a mechanical position. By controlling the stator flux linkage vector properly, the required torque can be produced with a fast response time.

The use of switching table with zero voltage vectors revealed loss of control, which could not attributed to factors such offsets in measurement and variation of stator resistance which are known sources of problems for the DTC.

The eight voltage vectors switching table is found to be preferable for high speed operating conditions with lower torque and stator flux ripples. The main advantages of the proposed structure are:
- Stable and efficient structure.
- Improvement of torque ripple characteristic in a large speed range.
- Fast response and robustness merits entirely preserved.

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