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Control of permanent-magnet synchronous motor using a novel switching-table-based DTC with zero-voltage vectors

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***Abstract* - Permanent-magnet synchronous machines have found large use due to their high efficiency and easy control implementation. Along with pulse width modulation variable speed drives and field-oriented control, permanent-magnet synchronous motors meet the most demanding needs of industry. In this manuscript, we present a novel switching table that improves direct torque control of a permanent magnet synchronous motor while keeping switching frequency minimal. The use of zero-voltage vectors in the standard method with a three-level hysteresis switch for torque control leads to current deviation and poor flux control, which disturbs the normal behavior of the machine. The switching table proposed in this manuscript gives better flux control with minimal switching frequency as supported by simulation results.**

Index Terms - Direct torque control (DTC), Permanent-magnet synchronous motor (PMSM), Switching table, Torque ripple minimization, Two and three level hysteresis controller, Zero Voltage Vectors.

INTRODUCTION

Permanent-magnet synchronous motors have found widespread use due to their power density, high efficiency, ease of control and high torque-mass ratio [1-3]. In conjunction with pulse width modulation variable speed drives and field-oriented control, these motors meet the most demanding needs of industry. Motor drives with vector control are considered the most efficient to date. However, this control technique is complex, and highly sensitive to alternating current motor internal parameters [4]. These difficulties have prompted research laboratories to consider other vector controls. One solution has been a technique called direct torque control or DTC [5], which offers better torque dynamics with relative simplicity compared to field-oriented vector control, now considered conventional. First introduced for asynchronous motors, the DTC controller can be applied to all AC motors. The original method proposed by Takahashi uses two hysteresis controllers: a two-level controller to adjust stator flux within limits of error and a three-level controller to regulate electromagnetic torque amplitude in real time [6]. This combination allows the use of all eight voltage vectors produced by the two-level inverter (including zero vectors).

However, in PMSM, because zero-voltage vectors are used, this configuration does not allow full control of stator flux. In fact, the flux no longer changes, even if its level falls outside the hysteresis band.

The use of zero-voltage vectors is important because it reduces both torque ripple and switching frequency of power semiconductor devices.

The use of zero-voltage vectors with only predictive control was still being investigated quite recently [7, 8]. In [9] an adaptive variable voltage vector switching table using zero voltage vectors was proposed but works only in one rotation direction, and adds some calculation to the processor. Other recent papers use complicated algorithms that are processor consuming to reduce torque ripple, or multi-level inverters, which costs more [10-16]. To the best of our knowledge, a switching table has never been investigated as a control method in this context. We present here a new voltage-vector switching table that provides better flux control, while maintaining motor performance and keeping switching frequency minimal.

TOOLS AND MATERIALS

I. PMSM modelling

The surface-mounted PMSM (with sine-wave EMF distribution) model is embodied in equations 1 and 2 respectively for voltage and torque, both expressed in the rotor-linked reference frame (d-q).

$$\begin{cases} V_d = R_s\, i_d - L_q \omega_s\, i_q + L_d \dfrac{di_d}{dt} \\ V_q = R_s\, i_q + L_d \omega_s\, i_d + L_q \dfrac{di_q}{dt} + \omega_s\, \varphi_r \end{cases} \quad (1)$$

$$C_{em} = p\,(\varphi_r i_q + (L_d - L_q)\, i_d\, i_q) \quad (2)$$

φ_r The flux linkage due to the rotor magnets linking the stator (Wb)
Rs The stator resistance (Ω)
Ld and Lq The direct and quadratic axis stator inductances (H)
P The number of pole pairs of the machine (dimensionless)
id and iq The direct and quadratic currents (A)
vd and vq The direct and quadratic voltages (V)
ωs The synchronism speed (rad/s)
Equations 1 and 2 are obtained using Park-Concordia transformation, which converts a three-phase system into an equivalent two-phase system linked to a rotating reference frame, as illustrated in Figure 1.

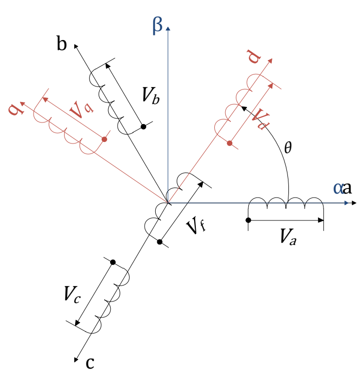

FIGURE 1
REFERENCE FRAMES (ABC), (AB) AND (DQ)

II. Conventional direct torque control

The direct torque control method is based on estimating flux as the integral of stator electromotive force. Torque is calculated using measured current and the estimated flux. The only machine parameter that needs to be known is the stator resistance, which can be ignored at high speeds because its voltage drop is negligible [17]. The switching vectors are obtained from a predefined table, thus simplifying control, and reducing calculation time [18].

Electromagnetic torque Ce can be expressed using equation 3. Its range of variation can be computed using equation 4 with stator flux amplitude variations neglected.

$$C_e = \frac{p}{L_s}\varphi_s\varphi_r \sin\delta \quad (3)$$

$$\Delta C_e = \left(\frac{p}{L_s}\varphi_s\varphi_r \cos\delta\right)\Delta\delta \quad (4)$$

Ls The stator inductance (H)
φs The stator flux (Wb)
δ The load angle between φs and φr (rad)
Equation 4 shows that δ and torque vary proportionately. Torque therefore can be controlled using the stator flux rotational speed.
Stator flux can be estimated using equation 5:

$$\varphi_s = \int (V_s - R_s I_s)dt \quad (5)$$

Neglecting resistive voltage drops, the flux can be computed using equation 6.

$$\varphi_s = \int V_s dt \quad (6)$$

Flux clearly depends on the applied voltage vector. Over very short time intervals, equation 7 can be assumed true.

$$\Delta\varphi_s = V_s\Delta t \quad (7)$$

The control of flux using voltage vectors is illustrated in Figure 2. The flux vector follows the trajectory traced by the applied voltage vector [19]. The voltage direct component clearly increases the amplitude of the flux, whereas the quadratic component increases the amplitude of the torque.

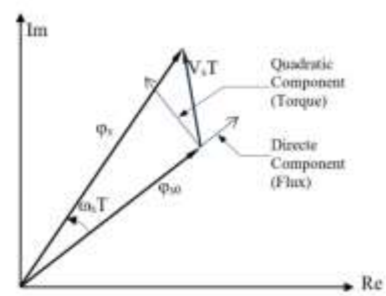

FIGURE 2
CONTROL OF STATOR FLUX BY VOLTAGE VECTORS

METHODOLOGY

I. Classic DTC controller implementation

The complex plane is divided into six areas spanning angles of π/3. The flux vector can be in any of the six areas, as illustrated in Figure 3.

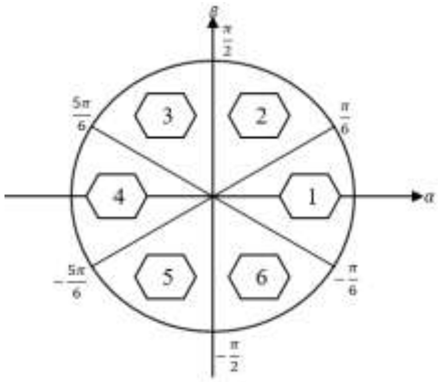

FIGURE 3
THE COMPLEX PLANE DIVIDED INTO SIX AREAS (AB)

Depending on the area and the dynamics of flux and torque, the applicable voltage vector V can be chosen to comply with the flux and torque set points. Three parameters are therefore available for vector selection. The truth table for choosing the right vector V according to the classical method [6] is as follows:

TABLE I
VOLTAGE VECTOR SELECTION TABLE FOR DTC

h_φ	h_C	$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	−1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	−1	V_5	V_6	V_1	V_2	V_3	V_4

Direct torque control of the synchronous motor is illustrated schematically in Figure 4. The hysteresis controllers are three-level for torque and two-level for flux.

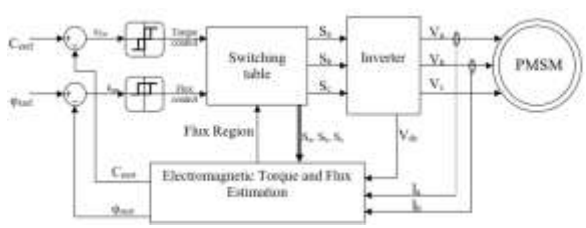

FIGURE 4
BLOCK DIAGRAM OF DIRECT TORQUE CONTROL OF A SYNCHRONOUS MOTOR

The conceptualization is simplified by using the stator side as a reference frame (α, β). Flux is estimated using the relationships defined in equations 8, and electromagnetic torque is computed using equation 9.

$$\begin{cases} \varphi_\alpha = \int (V_\alpha - R_s I_\alpha) dt \\ \varphi_\beta = \int (V_\beta - R_s I_\beta) dt \end{cases} \tag{8}$$

$$C_e = p.\left(\varphi_\alpha . I_\beta + \varphi_\beta . I_\alpha\right) \tag{9}$$

The speed controller is of the proportional/integral type. It generates the torque reference. The flux reference is calculated from the torque reference to satisfy the maximal torque per Ampere criterion implicit in equation 10 [19, 20].

$$\varphi_{sref} = \sqrt{\varphi_r{}^2 + \left(\frac{L_{sq} C_{eref}}{p \varphi_r}\right)^2} \tag{10}$$

II. Implementing the proposed hysteresis controller

It has been shown that the classic DTC controller for PMSM induces excessive disturbances of direct current due to poor flux control. Among the numerous solutions proposed to overcome this problem, we consider the following three:

a) Using a two-level torque hysteresis regulator. The drawbacks of this method are higher torque ripple and high switching frequency [21]. Most published studies of direct torque control of permanent-magnet synchronous motors focus on this approach.

b) Replacing the zero-voltage vectors of the DTC truth table (Table 1) by the active vectors of each specific area along with the opposite one as shown in Table 2, for example, vectors 1 and 4 instead of vectors 0 and 7 in area 1. This selection strongly effects flux with little effect on torque. The drawback of this method is the high switching frequency, which nullifies the advantage of using a three-level torque hysteresis regulator.

TABLE II
SWITCHING TABLE (HC3, HF2) WITHOUT ZERO VECTORS

h_φ	h_C	$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_1	V_2	V_3	V_4	V_5	V_6
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_4	V_5	V_6	V_1	V_2	V_3
	-1	V_5	V_6	V_1	V_2	V_3	V_4

c) Controlling flux while keeping switching frequency relatively low and torque ripple minimal, that is, the novel method proposed here. A three-level flux controller is introduced only in the case where the torque reaches its reference, meaning only when a zero-voltage vector is requested. Figure 5 shows the block diagram of the proposed controller, and Table 3 represents the required vector selection truth table. When the flux is far from its reference and the torque has reached its reference, the voltage vector chosen is not a zero vector but one of the two active vectors that act only on the flux.

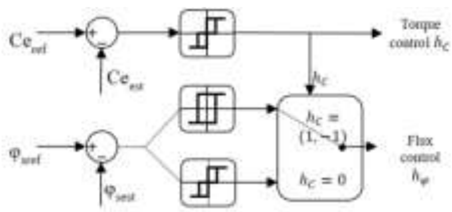

FIGURE 5
BLOCK DIAGRAM OF THE PROPOSED HYSTERESIS CONTROLLERS

TABLE III
NOVEL SWITCHING TABLE HC3, HF(2-3)

h_φ	h_c	$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	-1	V_3	V_4	V_5	V_6	V_1	V_2
0	1	V_1	V_2	V_3	V_4	V_5	V_6
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_4	V_5	V_6	V_1	V_2	V_3
-1	1	V_6	V_1	V_2	V_3	V_4	V_5
	-1	V_5	V_6	V_1	V_2	V_3	V_4

The tests were implemented on Matlab software considering a PMSM with the parameters presented in Table 4.

TABLE IV
PARAMETERS OF THE PMSM

Parameter	Value (Unit)
p	3
R	1.4 (Ω)
Ld	5.6e-3 (H)
Lq	5.8e-3 (H)
φr	0.1893 (Wb)
J	0.00176 (kg·m^2)
b	388e-6 (N·m·s/rad)
Nn	1000 (rpm)
Cn	6.1 (N·m)
Cemax	20.7 (N·m)

RESULTS AND DISCUSSION

I. Classic DTC results

Figures 6 to 9 represent the speed, flux, direct current, and electromagnetic torque responses of the PMSM controlled using conventional DTC. The reference speed is 1000 rpm between 0 s and 0.05 s, and -1000 rpm between 0.05 s and 0.1 s. A nominal torque load is applied between 0.03 s and 0.08 s.

The start-up flux and the damping of the disturbance when the load is applied are satisfactory. Electromagnetic torque is entirely coherent with its reference. However, a flux disturbance is apparent during the transient (Figure 7) at start-up and when the direction of rotation is reversed. Flux and its reference are incoherent with each other, which results in an increase in the direct current id as shown in Figure 8.

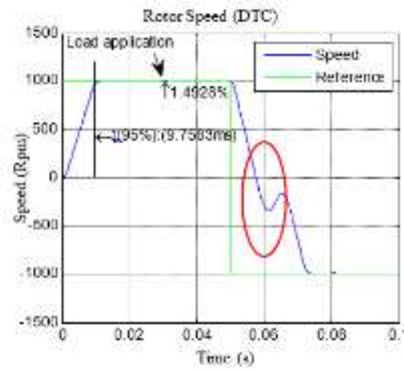

FIGURE 6
PMSM ROTOR SPEED UNDER CONVENTIONAL DIRECT TORQUE CONTROL

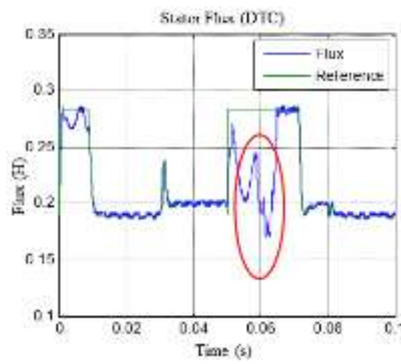

FIGURE 7
PMSM FLUX AMPLITUDE UNDER CONVENTIONAL DIRECT TORQUE CONTROL

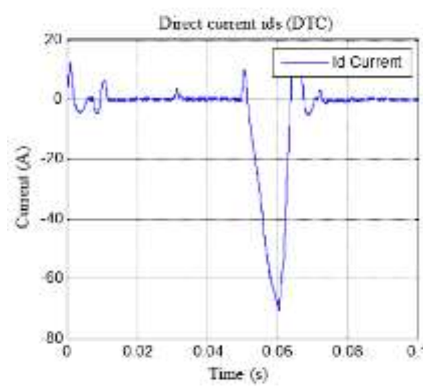

FIGURE 8
DIRECT CURRENT (ID) UNDER CONVENTIONAL DIRECT TORQUE CONTROL

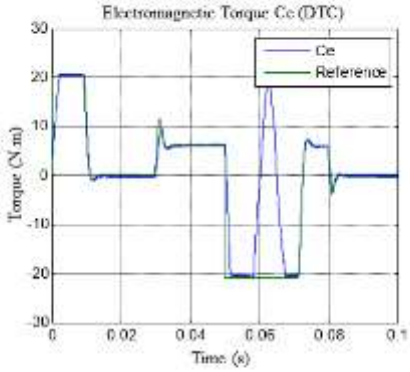

FIGURE 9
ELECTROMAGNETIC TORQUE UNDER CONVENTIONAL DIRECT TORQUE CONTROL

The observed disturbance is due to the use of zero-voltage vectors [22, 23], which does not allow the stator flux to reach its reference value at the same speed as the torque. The use of zero-voltage vectors in the three-level torque regulator slows down the evolution of the flux towards its reference, and causes a disturbance in the direct current, which affects the torque, thereby causing a speed disturbance.

II. Performance of the proposed hysteresis controller

To overcome the disturbance mentioned above, a two-level/three-level control scheme is implemented. The test scenario consists of a no-load start and a load applied at 0.03 s. Figure 10 shows the change in PMSM speed during a speed reversal.

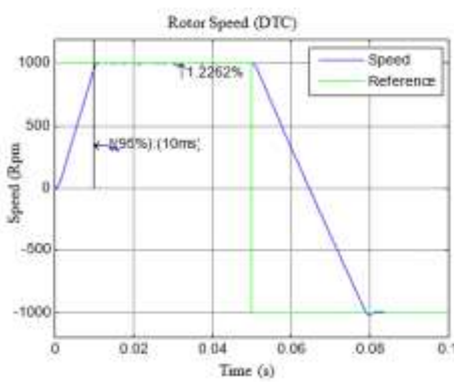

FIGURE 10
PMSM SPEED UNDER CONTROL BY THE HC3, HF(2-3) SCHEME

It is important to note that the speed follows the reference and that the disturbance of the torque is well damped. Electromagnetic torque (Figure 11) is coherent with its reference and the stator flux follows a circular path in the complex plane as illustrated in Figure 12 with a close-up on the two-level and three-level hysteresis operation effect. The switching states are summarized in Table 5.

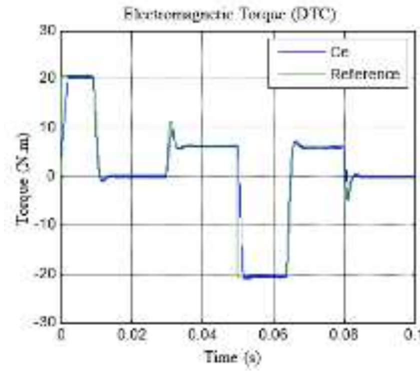

FIGURE 11
ELECTROMAGNETIC TORQUE UNDER CONTROL BY THE HC3, HF(2-3) SCHEME

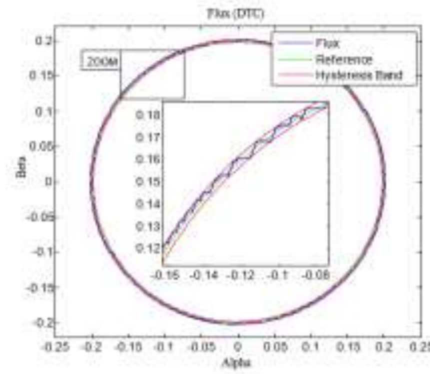

FIGURE 12
ELECTROMAGNETIC TORQUE UNDER CONTROL BY THE HC3, HF(2-3) SCHEME

TABLE V
SWITCHING STATES OF THE INVERTER

$V_0(0,0,0)$	$V_1(1,0,0)$	$V_2(1,1,0)$	$V_3(0,1,0)$
$V_4(0,1,1)$	$V_5(0,0,1)$	$V_6(1,0,1)$	$V_7(1,1,1)$

Table 6 summarizes switching frequencies in the different methods. The frequency under the conditions of the proposed method is close to that of the two-level case, due mostly to transient conditions. The more the motor runs under constant conditions, the lower the frequency will be.

TABLE VI
SWITCHING FREQUENCIES USED IN THE TESTED METHODS

DTC hysteresis regulator configuration	Mean switching frequency (Hz)
Two-level HC2 HF2	13,577
HC3 HF2 without zero voltage vectors	23,254
Proposed HC3, HF(2-3)	**12,917**

CONCLUSION

We have modeled and tested in simulation a novel method of direct torque control of a permanent magnet synchronous motor. A three-level hysteresis controller can be used to reduce torque ripple and minimize the switching frequency of the inverter switches. However, this solution alone does not allow full flux control during extreme transient conditions such as speed reversal with full load. A solution that combines two-level and three-level hysteresis control including zero-voltage vectors was implemented successfully using a truth table that helped to control flux perfectly without compromising performance. Motor speed was controlled adequately at its set point with minimal overshooting while torque control was excellent.

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