Extension of the DTC Technique to Multiphase Induction Motor Drives using any Odd Number of Phases

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***Abstract*—The interest of Direct Torque Control (DTC) methods in conventional three-phase induction motor drives has been stated by the scientific community and the industry in the very recent decades. Multiphase electric drives have also been recently proposed for applications where the highest overall system reliability and power distribution per phase are required, being transportation systems one of these applications. The DTC technique has been extended to the multiphase drive case at a higher computational cost than in the three-phase case, particularly the symmetrical five-phase and asymmetrical six-phase induction machines. This paper extends for the first time the use of DTC in *n*-phase induction machines, being '*n*' any odd number higher than three. The strategy for this extension to any *n*-phase induction machine is presented, and simulation results are provided to illustrate the interest of the proposed technique.**

Keywords—Multiphase induction motor drives; direct torque control method.

I. INTRODUCTION

High performance applications in conventional three-phase electromechanical AC drives require specific control systems. The most common control structure is the well-known Field Oriented Control (FOC) technique, a cascaded scheme with an inner current control loop and an outer speed control loop [1]. The inner control loop typically generates switching signals for control of a two-level voltage source inverter (VSI). The VSI is controlled using an appropriate carrier based or space vector PWM. However, other control methods namely DTC and Predictive Torque Control (PTC) have been more recently proposed when fast torque dynamic performance is demanded [1,2]. This is particularly interesting in the case of DTC developed in the mid-1980s due to its simplicity. Its basic principle is to select the appropriate stator voltage vectors from a table, according to the signs of the errors between the references of torque and stator flux and their estimated values, respectively [1]. In addition, the PTC is a control theory developed at the end of the 1970s that also provides fast torque response, but it is a more flexible control scheme. PTC determines and applies during a sample time the optimal set of VSI switching states, based on a model of the real system [2].

Multiphase drives are nowadays under consideration of the scientific community because they offer interesting characteristics when compared to their three-phase counterparts, like better fault tolerance and power-per-phase distribution [3, 4]. These advantages are especially interesting for propulsion applications, like electrical and hybrid vehicles, ship propulsion or more-electric aircrafts [3-5], due to their fault tolerance and higher reliability, or the higher power splitting across the different phases. For instance, if one of the phases is lost, it is no longer possible to maintain the rotating field in the three-phase machine while multiphase drives offer a system reliability improvement. However, multiphase drives normally require the extension of the control strategies from the three-phase case, which it is not a simple process coming to complex control algorithms. FOC, DTC and PTC have been recently extended from the three-phase to the multiphase case [6-11]. While FOC has been extensively applied with success in multiphase drives [6, 7], DTC and PTC have been also used to a lesser extent in five- and six-phase drives obtaining faster dynamic torque responses [8-11].

In our work, the DTC technique is extended for the first time to any *n*-phase induction machine, being n any odd number higher than 3 and considering sinusoidal winding and magneto motive force distribution. Then, the main contribution of this work is to prove the viability and effectiveness of DTC in high performance applications of any multiphase electrical drive. The paper is organized as follows. First, the general principles of the extension of the DTC method for a particular multiphase drive, a five-phase induction motor drive, are introduced in Section II. Then, section III analyzes the extension of DTC to a more general multiphase induction motor drive with any odd number of phases. As the number of phases increases, the available voltage vectors to be applied using DTC also increase, making more complex the extension of the DTC technique to a more general *n*-phase induction machine. The problem is stated in section III and some guidelines are presented to make viable the extension of DTC to a general multiphase induction motor drive. The performance of the DTC method is discussed using simulation results in Section IV, comparing with those obtained using a five-phase induction motor drive and described in the scientific literature. Finally, the conclusions are presented in the last section.

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II. DTC IN FIVE-PHASE DRIVES

The extension of the DTC control scheme for five-phase induction motor drives presented in [8,12] is improved in [13], where two-level flux and three-level torque comparators are proposed to provide the control action. Additionally, a low-speed region (speed less than a limit designed by ω_{rth}) is considered in the control strategy to mitigate the neglected stator resistance effect. Figure 1 summarizes the DTC control scheme proposed in [13]. Instead of discrete switching states, ten different active virtual vectors in the α-β subspace are also established for control purposes. These virtual vectors are obtained using one medium and one large size space vectors in the α-β subspace (medium and small size vectors, opposite in phase in x-y subspace, respectively) with proper dwell time ratio to generate zero average volts-per-seconds in the x-y subspace. The α-β subspace is then divided into ten sectors as it is shown in Fig. 2(a), and the x-y subspace is omitted from the extension of the DTC strategy to the multiphase case where virtual vectors in the α-β subspace are defined like in the three-phase case. The normalized dwell times with respect to the applied sampling period T_s to generate the virtual vectors are $K_v = (3-\sqrt{5})/2$ for medium vectors, and $(1-K_v)$ for large vectors. The synthesized vectors have a magnitude of $((5-\sqrt{5})/2)\cdot V_{dc}$. The DTC technique for the five-phase case proposed in [13] uses the look-up table shown in Table I.

III. EXTENSION OF DTC TO A GENERAL MULTIPHASE INDUCTION MOTOR DRIVE

In this section, the DTC method is analyzed when it is used in a multiphase induction machine with n-phases, being 'n' any odd integer number greater than 3. The extension of the DTC technique to a general multiphase induction machine should be similar to the five-phase case, using the virtual vectors' definition methodology. However, as the number of phases increases, the number of subspaces also increases (from two subspaces in the 5-phase case to three in the 7-phase case, and so on). Then, it is required to extend the zero average volts-per-second strategy in all the subspaces rather than the α-β one (those that do not contribute to the electrical torque generation in a distributed winding multiphase induction machine). This is done generating virtual vectors with dwell times as stated in eq. (1).

$$K_v^f = \frac{\sin(f\pi/n)\sin(\pi/n)}{\cos^2(\pi/2n)} \tag{1}$$

where n is the number of phases of the electrical machine (any odd number greater than 3) and f is the set of integers from 1 to $(n-1)/2$ with an increment of 1. For example, a five phase machine (n=5) has a set f={1,2}; a seven phase machine (n=7) has a set f={1,2,3}; f={1,2,3,4} in a nine phase machine (n=9), and so on. Notice that the virtual vectors (VV_j) generated in the five-phase induction motor drive case, using medium (V_m) and large (V_l) voltage vectors in the α-β subspace, is given by eq. (2), as it was stated in [13]. These virtual vectors can be generated in the multiphase case in a quite similar way. For example, virtual vectors can be generated using small (V_s), medium and large voltage vectors in the α-β subspace in the seven-phase case, as it is stated in eq. (3).

$$VV_j = V_m K_v^1 + V_l K_v^2 \tag{2}$$

$$VV_j = V_s K_v^1 + V_m K_v^2 + V_l K_v^3 \tag{3}$$

being j=1, 2, 3, …. $2n$. The generated virtual vectors in the α-β subspace and the generic n-phase case is stated in eq. (4), where sub indexes 1, 2,... identify voltage vectors from the smallest (1) to the largest $\left(\frac{n-1}{2}\right)$.

$$VV_j = V_1 K_v^1 + V_2 K_v^2 + V_3 K_v^3 + \dots\dots\dots + V_{\left(\frac{n-1}{2}\right)} K_v^{\left(\frac{n-1}{2}\right)} \tag{3}$$

A multiphase induction machine with 'n' number of phases, being n any odd number, has $2\cdot n$ active virtual vectors and two zero vectors. For example, in a five phase induction machine, ten non-zero virtual vectors appear (V_1 to V_{10} in Fig. 2a), while in the particular case of a seven-phase induction motor drive, there are fourteen non-zero virtual vectors (V_1 to V_{14} in Fig. 2b). Notice that if the number of phases increases, a redundancy also appears when selecting the virtual vectors to be used in different speed conditions [13]. For example, the virtual vectors V_2, V_5, V_7, and V_{10} are used for low speed operation if the stator flux is in sector 1 in the five-phase case, while the virtual vectors V_3, V_4, V_8, and V_9 are used for high speed operation (see Fig. 3 and [13]). This added difficulty in the DTC controller for the five-phase induction motor drive increases with the number of phases. For example, the virtual vectors V_2, V_7, V_9, and V_{14} can be used in the seven-phase induction motor drive case and the low-speed operation region, Fig. 4a. However, if the high-speed operation region is considered, two different possibilities appear and the set of the applied virtual vectors can be V_3, V_6, V_{10}, and V_{13} (called from now on Near Virtual Vectors' set or NVV, Fig. 4b) or V_4, V_5, V_{11}, and V_{12} (Far Virtual Vectors' set FVV in what follows, Fig. 4c). As the number of phases increases, more sets of applied virtual vectors appear and the DTC controller becomes more complex, Fig. 2c. This paper focuses on analyzing this added difficulty in the DTC controller presented in [13], extending their proposal to any n-phase induction motor drive with any odd number of phases (seven phases in particular). The proposed DTC technique for the seven-phase case uses the look-up table detailed in Table II, and Table III shows the look-up table for the generic n-phase induction motor drive case (being n any odd number higher than 3).

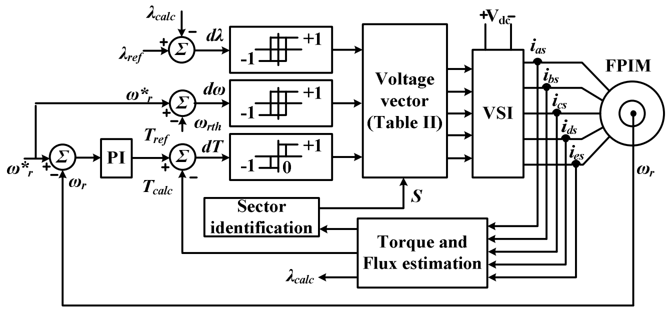

Fig. 1. DTC control sccheme presented in [13] for five-phase Induction Motor Drives.

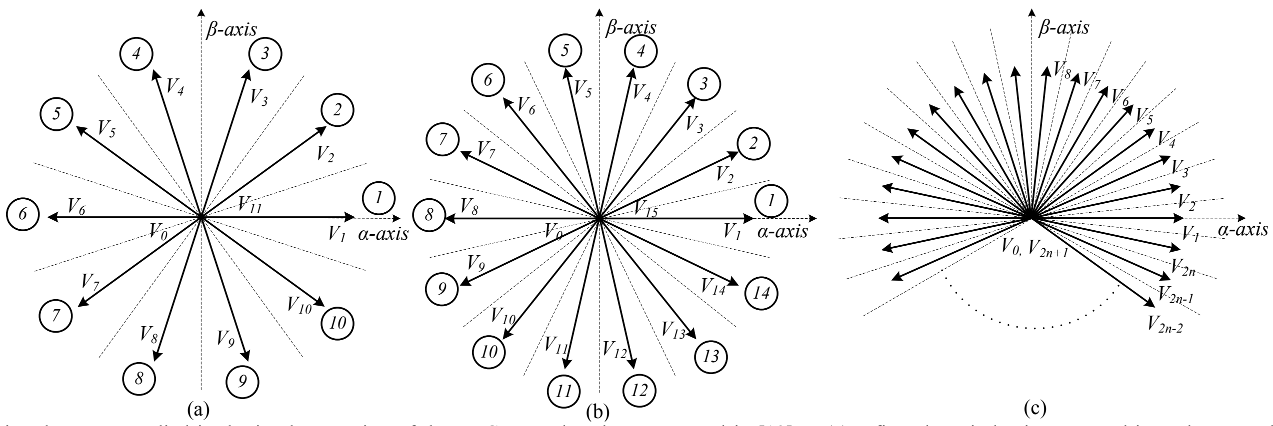

Fig. 2. Virtual vectors applied in the implementation of the DTC control scheme propoed in [13] to (a) a five-phase induction motor drive. The normalized dwell times with respect to the applied sampling period T_s to generate the virtual vectors are $K_v = (3-\sqrt{5})/2$ for medium vectors, and $(1 - K_v)$ for large vectors. The synthesized vectors have a magnitude of $((5-\sqrt{5})/2)\cdot V_{dc}$. Virtual vectors that can be applied in a general multiphase induction drive with any odd number of phases (b) seven-phase drive case, and (c) generic *n*-phase drive with any odd number of phases '*n*' greater than 3.

TABLE I. LOOK-UP TABLE FOR THE DTC CONTROLLER OF THE FIVE-PHASE INDUCTION MOTOR DRIVE

$d\omega_r$	$d\lambda_s$	dT_e	Position of stator flux (Sector)									
			1	2	3	4	5	6	7	8	9	10
0	+1	+1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_1
		-1	V_{10}	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
		0	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}
	-1	+1	V_5	V_6	V_7	V_8	V_9	V_{10}	V_1	V_2	V_3	V_4
		-1	V_7	V_8	V_9	V_{10}	V_1	V_2	V_3	V_4	V_5	V_6
		0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0
+1	+1	+1	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_1	V_2
		-1	V_9	V_{10}	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8
		0	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}
	-1	+1	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_1	V_2	V_3
		-1	V_8	V_9	V_{10}	V_1	V_2	V_3	V_4	V_5	V_6	V_7
		0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0	V_{11}	V_0

TABLE II. LOOK-UP TABLE FOR THE DTC CONTROLLER OF THE SEVEN-PHASE INDUCTION MOTOR DRIVE

$d\omega_r$	$d\lambda_s$	dT_e	Position of stator flux (Sector)													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	+1	+1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_1
		-1	V_{14}	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}
		0	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}
	-1	+1	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_1	V_2	V_3	V_4	V_5	V_6
		-1	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8
		0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0
+1	+1	+1	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_1	V_2	V_3
		-1	V_{12}	V_{13}	V_{14}	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}
		0	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}
	-1	+1	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_1	V_2	V_3	V_4
		-1	V_{11}	V_{12}	V_{13}	V_{14}	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}
		0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0	V_{15}	V_0

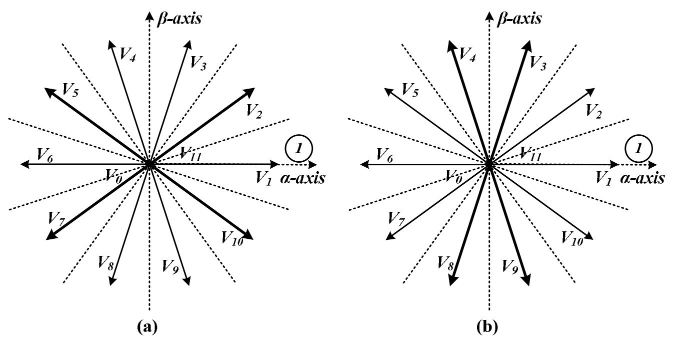

Fig. 3. Selection of virtual vectors (thicker lines) in a 5-phase IM drive using DTC, as stated in [13]. The flux vector is supposed in sector 1 at (a) lower speeds ($\omega_r < \omega_{rth}$) and at (b) higher speeds ($\omega_r > \omega_{rth}$).

IV. PERFORMANCE RESULTS

The proposed DTC scheme is implemented using a five-phase and a seven-phase induction motor drive and a Matlab/Simulink environment. The electrical and mechanical parameters of the multiphase induction machines are detailed in Table IV. The obtained simulation results are summarized in Figs. 5 to 7. These results were obtained using a DC link voltage of 400 V (V_{dc}=400 V), and the threshold value for separating the lower and higher speed regions of operation (ω_{rth}) was assumed to be a 10% of the motor rated speed. Notice also that the torque and flux hysteresis bands were programmed to be 1.25% and 1.43% of the rated values, respectively. The proportional and integral constants of

TABLE III. LOOK-UP TABLE FOR THE DTC CONTROLLER OF A GENERIC INDUCTION MOTOR DRIVE WITH A NUMBER OF ODD PHASES HIGHER THAN 3

$d\omega_r$	$d\lambda_s$	dT_e	Position of stator flux (Sector)											
			1	2	3	……	n-1	n	n+1	n+2	……	……	2n-1	2n
0	+1	+1	V_2	V_3	V_4	……	V_n	V_{n+1}	V_{n+2}	……	……	……	V_{2n}	V_1
		-1	V_{2n}	V_1	V_2	……	……	……	V_n	V_{n+1}	V_{n+2}	……	V_{2n-2}	V_{2n-1}
		0	V_0	V_{2n+1}	V_0	V_{2n+1}	……	……	……	……	……	……	V_0	V_{2n+1}
	-1	+1	V_n	V_{n+1}	V_{n+2}	……	……	……	V_{2n}	V_1	V_2	……	V_{n-2}	V_{n-1}
		-1	V_{n+2}	V_{n+3}	V_{n+4}	……	V_{2n}	V_1	V_2	……	……	……	V_n	V_{n+1}
		0	V_{2n+1}	V_0	V_{2n+1}	V_0	……	……	……	……	……	……	V_{2n+1}	V_0
+1	+1	+1	$V_{\frac{(n+1)}{2}}$	$V_{\frac{(n+1)}{2}+1}$	$V_{\frac{(n+1)}{2}+2}$	……	……	……	……	V_{2n}	V_1	……	$V_{\frac{(n+1)}{2}-2}$	$V_{\frac{(n+1)}{2}-1}$
		-1	$V_{\frac{3(n+1)}{2}}$	$V_{\frac{3(n+1)}{2}+1}$	……	……	V_{2n}	V_1	V_2	……	……	……	$V_{\frac{3(n+1)}{2}-2}$	$V_{\frac{3(n+1)}{2}-1}$
		0	V_0	V_{2n+1}	V_0	V_{2n+1}	……	……	……	……	……	……	V_0	V_{2n+1}
	-1	+1	$V_{\frac{(n+1)}{2}+1}$	$V_{\frac{(n+1)}{2}+2}$	……	……	……	……	V_{2n}	V_1	V_2	……	$V_{\frac{(n+1)}{2}-1}$	$V_{\frac{(n+1)}{2}}$
		-1	$V_{\frac{3(n+1)}{2}-1}$	$V_{\frac{3(n+1)}{2}}$	……	V_{2n}	V_1	V_2	……	……	……	……	$V_{\frac{3(n+1)}{2}-3}$	$V_{\frac{3(n+1)}{2}-2}$
		0	V_{2n+1}	V_0	V_{2n+1}	V_0	……	……	……	……	……	……	V_{2n+1}	V_0

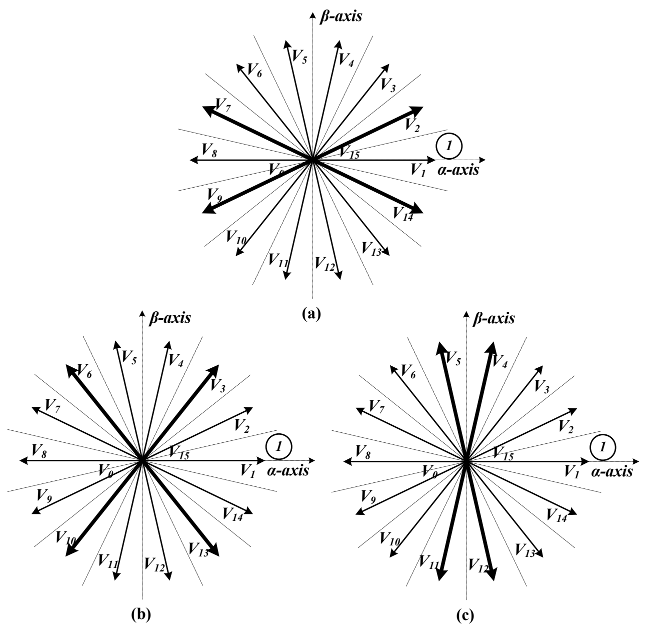

Fig. 4. Proposed selection of virtual vectors (thicker lines) in a 7-phase IM drive using DTC. The flux vector is supposed in sector 1 at (a) lower speeds ($\omega_r < \omega_{rth}$) and at higher speeds ($\omega_r > \omega_{rth}$) using (b) NVV and (c) FVV.

TABLE IV. INDUCTION MOTOR NOMINAL PARAMETERS

Parameter	*Value*	*Units*
Stator resistance, r_s	22.63	Ω
Rotor resistance, r_r	13.1	Ω
Stator leakage inductance, L_{ls}	102	mH
Rotor leakage inductance, L_{lr}	35.2	mH
Mutual inductance, M	588	mH
Moment of inertia, J	0.148	kg-m²
Number of pole pairs, P	3	--
Rated torque, T	8	N-m

the DTC speed controller were adjusted to be 2 and 7.5, respectively, using a trial and error procedure, and the control system was operated at a sampling frequency of 5 kHz.

The control performance of the proposed DTC controller is analyzed in the low speed (less than ω_{rth}) and the high speed (more than ω_{rth}) ranges of operation. Figure 5 shows the obtained results using a five-phase induction machine, and Fig. 6 presents the obtained results using a seven-phase induction machine. The upper plots depict the evolution of the mechanical speed of the multiphase drives and the middle plots show the stator flux evolution in the α-β and x-y subspaces, both in the low speed operation region. A reference speed step from 0 to 50 rpm is applied at 0.1 s, a load torque (T_L) of 50% of the rated value is imposed at 1 s, and a reversal reference speed command is forced at 2 s. The lower plots detail the evolution of the mechanical speed of the multiphase drives in the high speed operation region. A reference speed step from 0 to 500 rpm is applied at 0.1 s, a load torque (T_L) of 50% of the rated value is imposed at 2.5 s, and a reversal reference speed command is forced at 4 s. From aforementioned figures and plots it can be stated that similar speed and torque dynamics is obtained using the proposed DTC controller in a five-phase or a seven-phase induction motor drive with similar motor parameters, as it can be appreciated comparing Fig. 3(a) and Fig. 4(a) or Fig. 3(c) and Fig. 4(c). The middle plots in Figs. 5 and 6 show the obtained stator flux, which it is sinusoidal in the α-β subspace and nearly null flux in x-y subspaces. This is due to the generation of virtual vectors with proper dwell times, as indicated in eq. (1). The performance of the proposed DTC schemes (NVV and FVV) have been analyzed at high speed for the seven-phase drive case. Figure 7 summarizes the obtained results showing that the set of voltage vectors associated with the FVV method normally provides lower stator phase current THD when compared to that obtained using the set of voltages with the NVV technique. When the applied load torque increases, this difference is normally reduced, and the particular case where the total load torque is the nominal electrical torque of the machine is the unique one where NVV and FVV generate similar stator phase current THD.

V. CONCLUSIONS

The DTC scheme, typically used in conventional three-phase induction machines, has been very recently extended with success to the five-phase case. The proposed DTC technique is more complex than the normal DTC method to take into account the peculiarities of the multiphase drive and to reduce the harmonic content in the *x-y* subspace which do not contribute to the electrical torque generation. This paper analyzes the extension of the proposed DTC scheme from the five-phase induction motor drive to any multiphase induction machine with any odd number of phases greater than 3. While the proposal is similar in the low speed region, different sets of applied virtual vectors can be used at the high speed region, producing different THD in the stator phase current. For instant, two sets (named NVV and FVV) appear when the DTC technique is extended to the seven-phase induction motor drive case. The influence of using these different sets in the application of DTC to the seven-phase induction machine was analyzed at different operating point, comparing with the obtained results when DTC is applied to a five-phase induction drive, to conclude the superiority of the FVV method. This conclusion can be also extended to multiphase induction machines with an odd number of phases greater than 3 without any loss of generality.

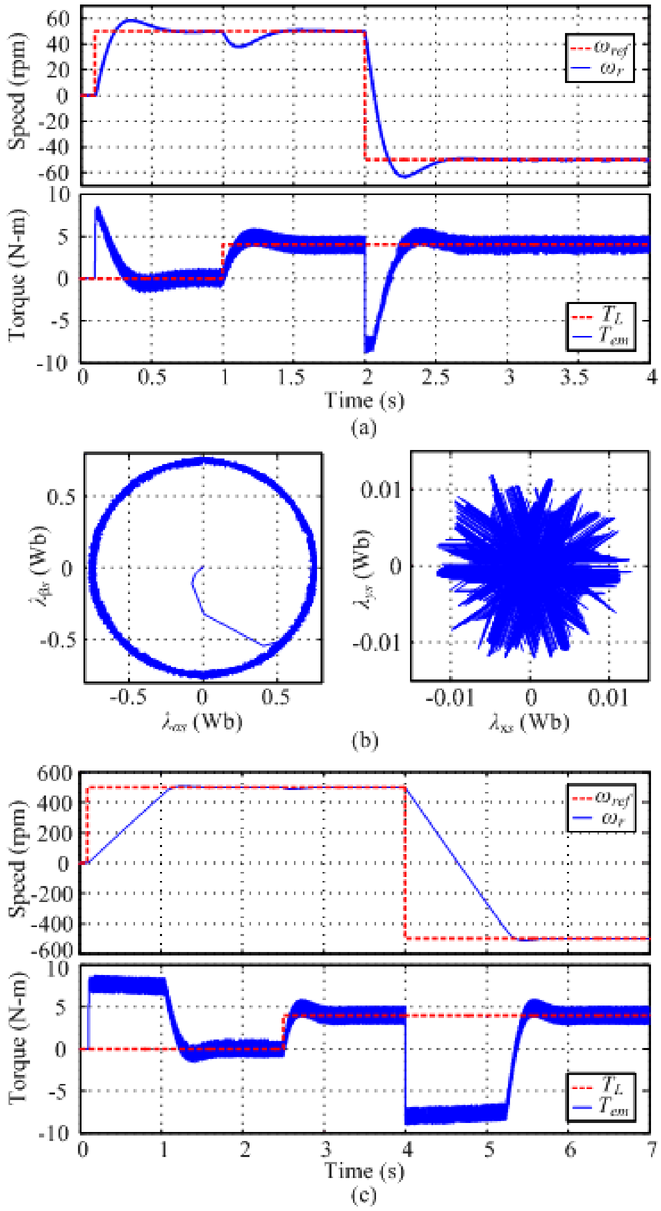

Fig. 5. Speed and torque response of a five-phase induction motor drive at low (a) and high (c) speed operation regions, and flux-linkage (b) in the *α-β* and *x-y* subspaces.

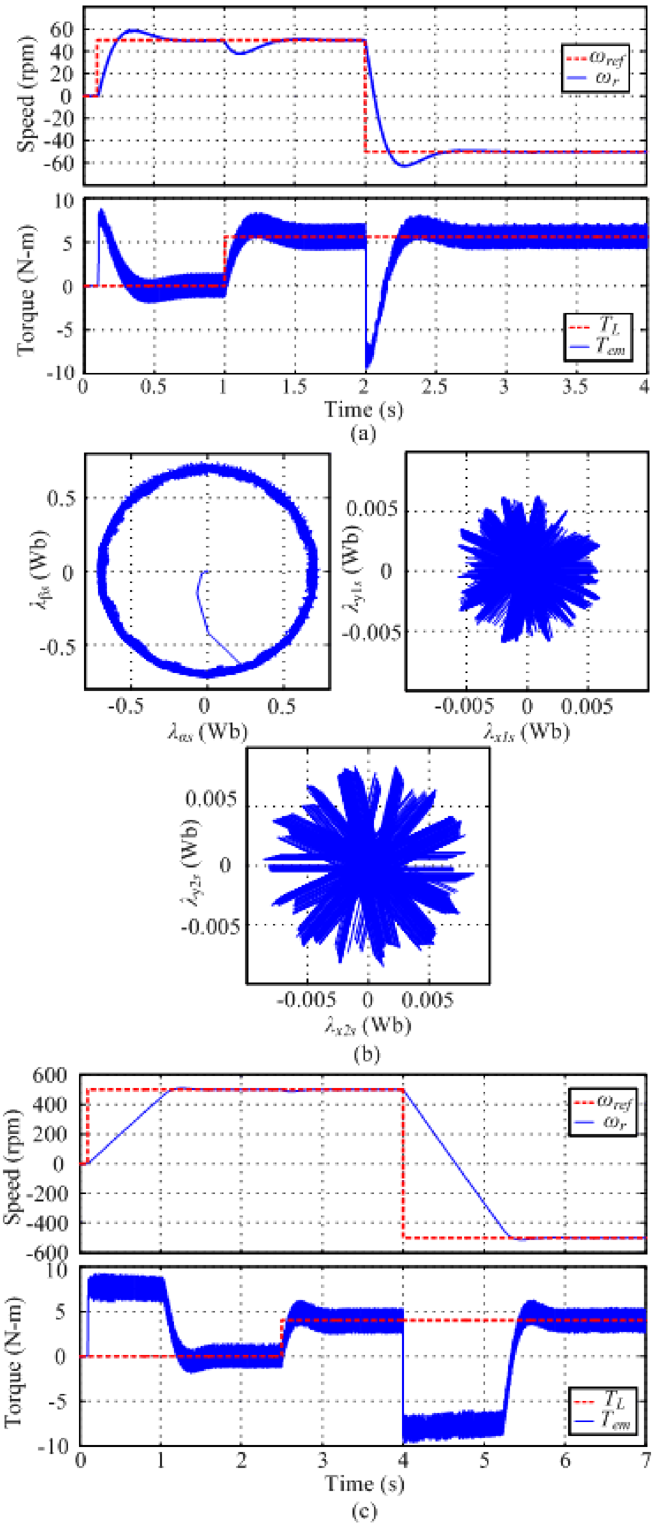

Fig. 6. Speed and torque response of a seven-phase induction motor drive at low (a) and high (c) speed operation regions, and flux-linkage (b) in the *α-β* and *x-y* subspaces. The FVV set of voltage vectors is used in the high speed region.

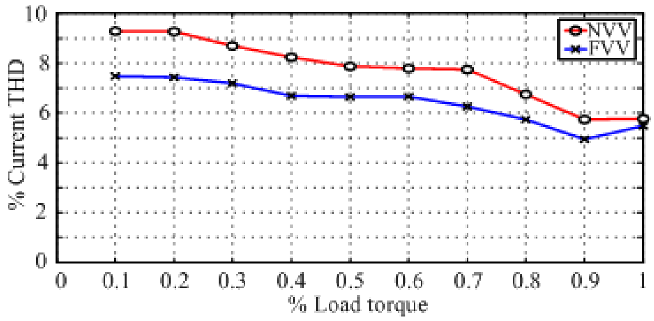

Fig. 7. Obtained harmonic distortion factors of a stator phase current at steady state using the proposed DTC controller in a 7-phase induction machine and applying the NVV or the FVV technique. THD is obtained considering three cycles of the stator phase current, at 500 rpm and varying the load from 10% to 100% of the nominal load.

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