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Mario BERMUDEZ GUZMAN, Hugo GUZMAN, Ignacio GONZALEZ PRIETO, Federico BARRERO, Mario Javier DURAN, Xavier KESTELYN - Comparative Study of DTC and RFOC Methods for the Open-Phase Fault Operation of a 5-Phase Induction Motor Drive - In: IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, Japon, 2015-11 - IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society - 2015

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Comparative Study of DTC and RFOC Methods for the Open-Phase Fault Operation of a 5-Phase Induction Motor Drive

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Abstract—Direct Torque Control (DTC) technique has been applied in recent times in high performance five-phase induction motor drives during the normal operation of the system. The use of DTC in the multiphase area is far from becoming a reality because it has not been used in competitive multiphase applications where the fault operation needs to be considered. The authors have successfully tested the ability of DTC controllers to manage the open-phase fault operation in a five-phase induction motor drive. However, the conclusion of the mentioned study must be completed comparing the obtained results with other mature alternatives based on field oriented controllers. This paper focuses on the comparative analysis of DTC and Rotor Field Oriented Control (RFOC) when an open-phase fault appears in the five-phase induction motor drive. Simulation results are provided to compare the performance of the system using these control alternatives.

Keywords— *Multiphase induction motor drives; Direct Torque Control (DTC); Rotor Field Oriented Control (RFOC); Open-phase fault operation.*

I. INTRODUCTION

The interest of the scientific community in the multiphase machine field is not new and has gained importance in recent times thanks to the development of modern microprocessors and power converters [1–2]. High performance multiphase drives are now recognized like an alternative to conventional three-phase ones in applications where the reduction of the power per phase and a high fault-tolerant capability are required. The symmetrical five-phase induction machine is one of the most interesting multiphase machines, and control methods normally applied in high performance three-phase induction drives have been extended to five-phase ones to exploit their advantages.

Different speed and torque control methods have been proposed in recent research works for the development of high performance five-phase induction motor drives. RFOC method is the most common one, where the outer speed and torque controller is complemented with multiple inner current control loops [3] or with predictive current controllers [4–5]. DTC and predictive torque control (PTC) techniques have been also presented like alternative control methods in the development of high-performance five-phase induction motor drives [6–8].

Most of these studies are focused on the normal operation of the drive, but the capability of the controllers to manage the faulty operation of the system without adding extra hardware has been also considered in the last years to increase the interest of the industry in multiphase motor drives [2].

Different types of faults may appear in the electrical drive, including inverter and machine faults like short-circuits and open-circuits faults, being the fault tolerance against open-circuit faults the most analyzed case by far in the multiphase machine area [2]. A common feature of the proposed open-phase post-fault control schemes is the use of a RFOC method with the same outer PI speed controller than in normal operation, while the inner current control loops have been realized using different strategies [9–12]. For example, dual PI or resonant controllers are proposed in [9] to follow oscillating reference currents, while a model-based predictive controller is used in [10–11]. Both controllers are compared in [12], where the obtained results conclude that predictive control provides faster response and superior performance at low/medium speed operation being less resilient to fault detection delays and having higher current and torque ripples.

This work compares the performance of DTC and RFOC controllers when facing an open-circuit post-fault operation in a symmetrical five-phase induction machine. The paper is organized as follows. Section II summarizes the behavior of the five-phase induction machine system during the open-phase fault operation mode when DTC controllers are applied. Then, how RFOC methods face the fault operation of the multiphase drive is detailed in Section III. Finally, Section IV shows simulation results where the ability of both methods managing the post-fault operation of the drive is studied, and the conclusions are provided in the last section.

II. OPEN-PHASE FAULT OPERATION IN FIVE-PHASE INDUCTION MOTOR DRIVES AND DTC CONTROLLERS

If symmetrically distributed windings, uniform air gap, sinusoidal MMF distribution and neglectable magnetic saturation and core losses are considered, the normal five-phase induction machine can be modeled by a set of voltage equilibrium equations as it is stated in [13]. When an open-phase fault appears (Fig. 1), the behavior of the system notably

varies because the current in the faulty phase is zero and its voltage is given by the counter electromotive force (Back-EMF).

The model of the system must be then revised as it is shown in [10], where phase 'a' is assumed, without any lack of generality, as the faulty phase. In general terms and using the vector space decomposition (VSD) approach to refer the system into the well-known α - β - x - y stationary reference frame, non-circular α - β current components are obtained using the VSD normal transformation (T_0), while circular α - β current components can be obtained using the modified VSD transformation shown in [10] and characterized by the T_{PCC} matrix, see (1) and (2). The current components that contribute to the torque production (those mapped in the α - β plane) are sinusoidal in post-fault operation and the system can be modeled in open-phase fault operation using the modified VSD transformation from the matrix equations in phase coordinates (3)-(6).

$$[T_0] = \frac{2}{5} \begin{bmatrix} 1 & \cos(\vartheta) & \cos(2\vartheta) & \cos(3\vartheta) & \cos(4\vartheta) \\ 0 & \sin(\vartheta) & \sin(2\vartheta) & \sin(3\vartheta) & \sin(4\vartheta) \\ 1 & \cos(2\vartheta) & \cos(4\vartheta) & \cos(\vartheta) & \cos(3\vartheta) \\ 0 & \sin(2\vartheta) & \sin(4\vartheta) & \sin(\vartheta) & \sin(3\vartheta) \\ 1/2 & 1/2 & 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (1)$$

$$[T_{PCC}] = \frac{2}{5} \begin{bmatrix} \cos(\vartheta)-1 & \cos(2\vartheta)-1 & \cos(3\vartheta)-1 & \cos(4\vartheta)-1 \\ \sin(\vartheta) & \sin(2\vartheta) & \sin(3\vartheta) & \sin(4\vartheta) \\ \sin(2\vartheta) & \sin(4\vartheta) & \sin(\vartheta) & \sin(3\vartheta) \\ 1 & 1 & 1 & 1 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{sy} \\ v_{sz} \end{bmatrix} = \frac{V_{dc}}{4} [T_{PCC}] \cdot \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix} \cdot \begin{bmatrix} S_b \\ S_c \\ S_d \\ S_e \end{bmatrix} - \frac{L_m}{4} \frac{di_{s\alpha}}{dt} + \frac{L_m}{4} \frac{di_{r\alpha}}{dt} [T_{PCC}] \cdot \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{sy} \\ i_{sz} \end{bmatrix} = [T_{PCC}] \cdot [i_s] \quad (4)$$

$$[v_s] = [R_s] \cdot [i_s] + \frac{d}{dt} [\lambda_s] \quad (5)$$

$$= [R_s] \cdot [i_s] + [L_{ss}] \frac{d}{dt} [i_s] + \frac{d}{dt} [L_{sr}(\theta)] \cdot [i_r]$$

$$[v_r] = [R_r] \cdot [i_r] + \frac{d}{dt} [\lambda_r] \quad (6)$$

$$= [R_r] \cdot [i_r] + [L_{rr}] \frac{d}{dt} [i_r] + \frac{d}{dt} [L_{rs}(\theta)] \cdot [i_s]$$

where S_i denotes the available power converter switching states (being $S_i = 0$ if the lower switch is ON and the upper switch is OFF, and $S_i = 1$ if the opposite occurs), $[i_s]$ is the stator phase current vector, $[v_s]$ is the stator phase voltage vector, $[\lambda_s]$ is the stator phase flux vector, the electrical parameters of the machine (stator and rotor resistances and inductances) are included into $[R]$ and $[L]$ matrices, ϑ is an electrical degree of 72° , θ represents the instantaneous rotor azimuth with respect to the α -axis of the stationary reference frame, phase 'a' is

considered as the faulty open phase ($i_{sa} = 0$) and the lost control degree is modeled as $i_{sx} = -i_{sa}$. The reduction of the available power converter switching states (S_i), from $2^5=32$ in pre-fault to $2^4=16$ in post-fault situation, is detailed in [10] and summarized in Fig. 2(a).

DTC control technique has been very recently applied to five-phase induction motor drives in normal operation [6-7]. Its extension to the open-phase post-fault operation of the multiphase drive is introduced in [13], and the proposed control scheme is shown in Fig. 3. The control action is provided using an outer PI closed-loop speed controller and two inner electrical torque and stator flux regulators based on a two-level stator flux and a three-level electromechanical torque hysteresis comparators. Eight active virtual voltage vectors are defined in the α - β subspace, each one corresponding to a different sector (see Fig. 2(b)), combining two available voltage vectors to obtain zero average volts-per-seconds in the y direction. The proposed DTC technique uses the look-up table shown in Table I, which determines the applied virtual voltage vector depending on the $d\lambda_s$ and dT_e error signals, the hysteresis comparators and the flux position. Notice that the stator flux and the torque in the electrical machine are estimated using two observers and the healthy stator phase currents.

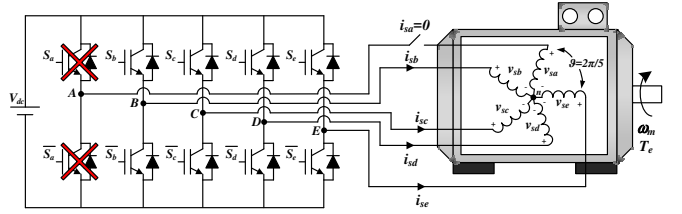


Fig. 1. Schematic diagram of the five-phase induction machine modeled, with a fault in phase 'a'.

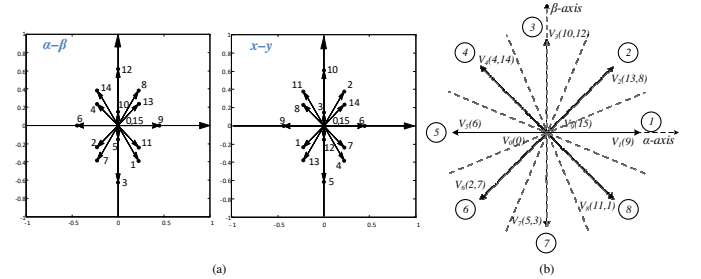


Fig. 2. (a) Available and (b) virtual voltage vectors in five-phase induction motor drives with the open-phase fault condition.

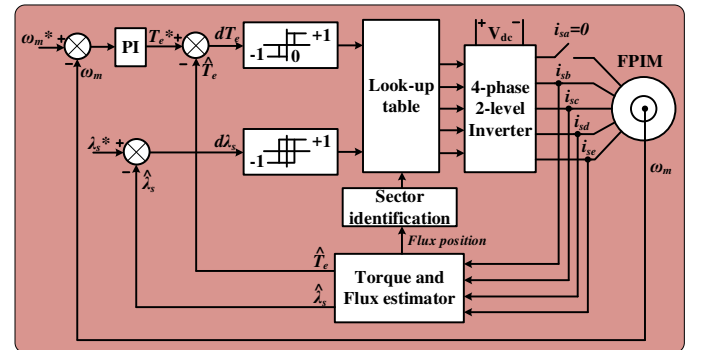


Fig. 3. DTC control scheme regulating the five-phase induction motor (FPIM) drive in open-phase fault situation.

TABLE I. LOOK-UP TABLE FOR THE DTC CONTROLLER IN POST-FAULT SITUATION PROPOSED IN [13]

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

III. RFOC MANAGING OPEN-PHASE FAULT OPERATION IN FIVE-PHASE INDUCTION MOTOR DRIVES

Other conventional three-phase control techniques have also been extended to the five-phase induction motor drive case, including also the open-phase fault operation. This is the case of the RFOC structure where different schemes have been proposed [9–12]. The controller is based on an outer PI closed-loop speed control and an inner fault-tolerant regulation considering proportional resonant (PR) regulators or finite-control set model-based predictive current controllers (PCC for now on). Fig. 4 shows a scheme of RFOC controllers applied in five-phase induction machines when the open-phase fault operation is also considered.

The speed and flux control is implemented in the d - q reference frame using conventional PI controllers. The d -current reference is set to a constant value while the q -current reference is determined using the speed error and a PI-based controller. Considering that the y -current component does not contribute to torque production, it is set to zero in order to minimize losses and improve the efficiency of the system [9–11]. As a consequence, it is not possible to achieve the maximum post-fault torque. The maximum reference currents in the α - β subspace can be obtained, using the five-phase drive maximum current ratings and imposing a rotating circle-shaped MMF, as follows:

$$i_{s\alpha}^{\max} = \frac{I_n}{k_1} \sin(\omega t) = 0.6813 \cdot I_n \sin(\omega t) \quad (7)$$

$$i_{s\beta}^{\max} = -\frac{I_n}{k_1} \cos(\omega t) = -0.6813 \cdot I_n \cos(\omega t)$$

The transformation into the α - β - x - y planes is done using T_0 in [9] (RFOC with PR controllers) and with T_{PCC} in [10–11] (RFOC with a PCC type current control method). The α - β current components are then mapped in the rotating d - q reference by means of the Park transformation and the position estimator that estimates the instantaneous rotor azimuth θ with respect to the α -axis:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (8)$$

$$\theta = \int \left(\omega_r + \frac{i_{sq}^*}{\tau_r \cdot i_{sd}^*} \right) dt \quad (9)$$

The sinusoidal nature of the post-fault x - y current references in RFOC methods results in the necessity of using PR regulators instead of conventional PI ones to control the oscillating terms. PR regulators are implemented in [9] adding

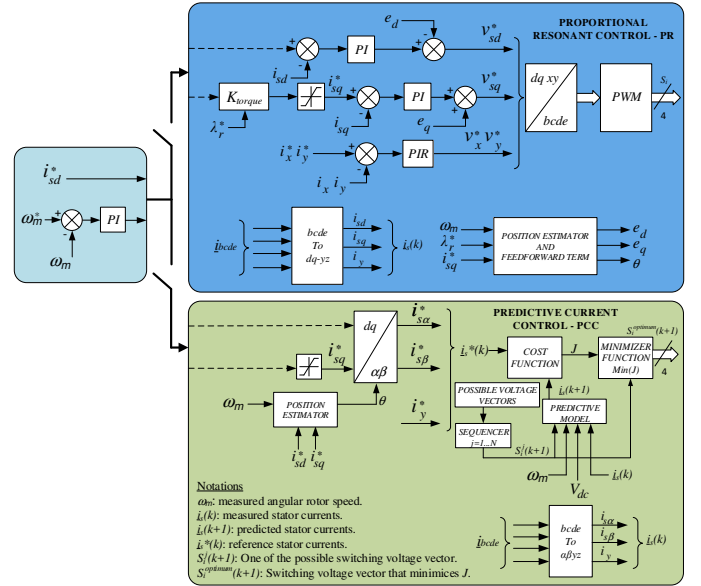


Fig. 4. RFOC control scheme based on proportional resonant (PR) regulators and PCC controllers.

the outputs of two independent PI controllers, rotating in the direct and the inverse direction of the field-oriented reference frame, tracking positive and negative sequence currents and driving to zero the total tracking error. The feed-forward terms (e_d and e_q) were included in the control scheme to improve the controller performance, where the rotor-flux estimator is based on the speed measurement and the d -current component, as shown in (10).

$$\frac{d}{dt} \lambda_r + \left(\frac{1}{\tau_r} - j\omega_m \right) \cdot \lambda_r = \frac{L_m}{\tau_r} \cdot i_{sd} \quad (10)$$

When the PCC technique is applied, the measured speed and stator currents are used with all available voltage vectors and the post-fault drive model to predict the stator current evolution for the next sampling period ($k+1$). The estimated stator current that minimizes a predefined cost function J defines the next voltage vector to be applied, which is the optimum voltage vector to be applied, $S_i^{\text{optimum}}(k+1)$. Different cost functions can be defined, although the most common one considers the difference between the reference and the predicted stator currents, as it is shown in (11) where different weighting factors are defined for α - β - x - y coordinates (A , B , C and D parameters). In [10] and [11] C is zeroed because the x -component stator current is $i_{sx} = -i_{s\alpha}$ (it cannot be regulated independently from the α -component stator current), while A , B and D are set to one.

$$J = A |i_{s\alpha}^*(k+1) - i_{s\alpha}(k+1)| + B |i_{s\beta}^*(k+1) - i_{s\beta}(k+1)| + C |i_{sx}^*(k+1) - i_{sx}(k+1)| + D |i_{sy}^*(k+1) - i_{sy}(k+1)| \quad (11)$$

IV. OBTAINED RESULTS

RFOC and DTC control methods are implemented in a five-phase induction motor drive modeled using a Matlab/Simulink environment. The electrical and mechanical

parameters of the multiphase induction motor drive (see Table II) are obtained from a real system using different identification techniques [14–15]. Figs. 5 to 9 summarize the obtained results, where a DC link voltage (V_{dc}) of 300 V is used.

Fig. 5 compares the speed responses of the system using DTC and RFOC controllers in the open-phase fault operation when the reference speed is first changed from 500 to 300 rpm, and then from 300 to 400 rpm. A load torque of 25% of the nominal one is used. Although similar speed responses are obtained (upper plot), a detailed analysis of the responses (lower figures) shows that the DTC controller (red traces) generates larger overshoots and poorer responses than the RFOC controllers with PCC technique (green traces), while offers similar responses than RFOC with PR controllers (blue traces). All the control techniques offer a similar performance when a change in the load torque is applied, as it is shown in Fig. 6, where the load torque is changed from 0 to 25% of the nominal one at 500 rpm. However, the speed responses when a reversal test is done (from 500 rpm to -500 rpm in Fig. 7) show again slightly better performances when RFOC method with PCC current controllers are used. These results prove that RFOC methods are not clearly superior to DTC techniques from the system performance perspective. Nevertheless, notice that the computational cost is much higher using RFOC methods, particularly if PCC technique is applied, which favors the real-time implementation of the DTC technique in modern microprocessors.

Fig. 8 shows the evolution of the stator currents in stationary frames using DTC and RFOC controllers in the open-phase fault operation when the reference speed is 500 rpm. The applied load torque is 25% of the nominal one. Again, the obtained results using the DTC controller, Fig. 8(c), are worst than the obtained using RFOC techniques, Figs. 8(a) and 8(b). The harmonic content (amplitude of the ripple in the circular plots) is superior using DTC in the α - β and x - y plane. Notice that the PR current controller offers the best performance in this test, Fig. 8(a). Fig. 9 depicts the evolution of the stator currents in stationary frames but using an applied load torque of 56% of the nominal one. The same conclusions are reached, showing that the DTC controller presents the worst response among the applied controllers. Notice that higher current ripples appear in this test comparing with the previous one, being this a consequence of approaching the maximum load torque that the speed controller can manage in the open-phase fault operation (about 64% of the nominal one, as it is shown in [10]).

TABLE II. ELECTRICAL AND MECHANICAL PARAMETERS OF THE ANALYZED FIVE-PHASE INDUCTION MOTOR DRIVE

Parameter	Value	Units
Stator resistance, R_s	12.85	Ω
Rotor resistance, R_r	4.80	Ω
Stator leakage inductance, L_{ls}	79.93	mH
Rotor leakage inductance, L_{lr}	79.93	mH
Mutual inductance, M	681.7	mH
Moment of inertia, J	0.02	kg-m ²
Number of pole pairs, P	3	--
Rated torque, T_n	4.70	N-m
Rated stator flux, λ_s^*	0.389	Wb

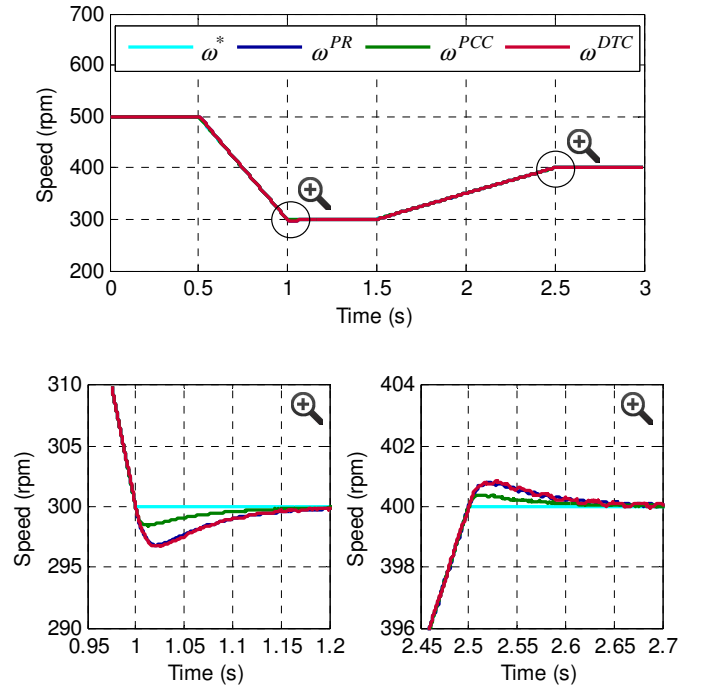


Fig. 5. Speed response in the five-phase induction motor drive when the reference speed is changed in the system using a load torque of about 25% of the nominal one.

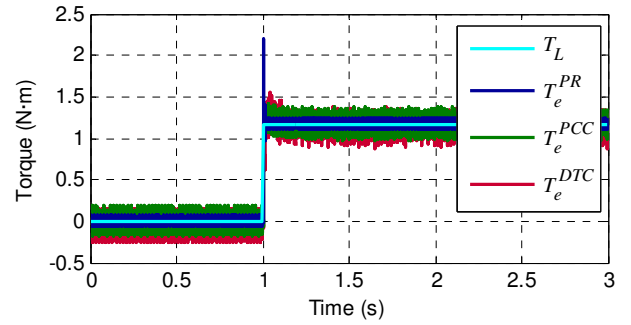


Fig. 6. Generated electrical torque in the five-phase induction motor drive when the load torque is changed from 0% to 25% of the nominal one. The reference speed is maintained at 500 rpm during the test.

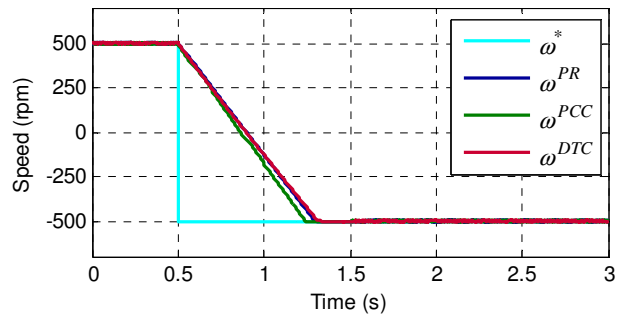


Fig. 7. Speed response using a reversal test from 500 to -500 rpm.

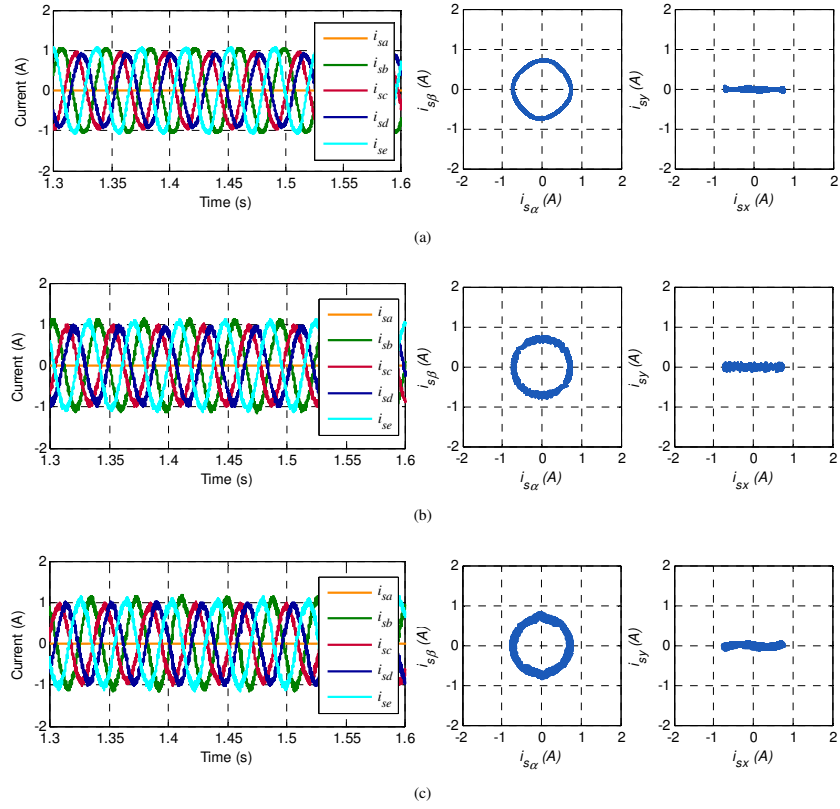


Fig. 8. Steady state operation. Stator phase currents (left hand side plots) and evolution in the α - β (middle plots) and x - y (right hand side plots) planes, with a reference speed of 500 rpm and a load torque of about 25% of the nominal one, implementing (a) PR, (b) PCC and (c) DTC controllers, respectively.

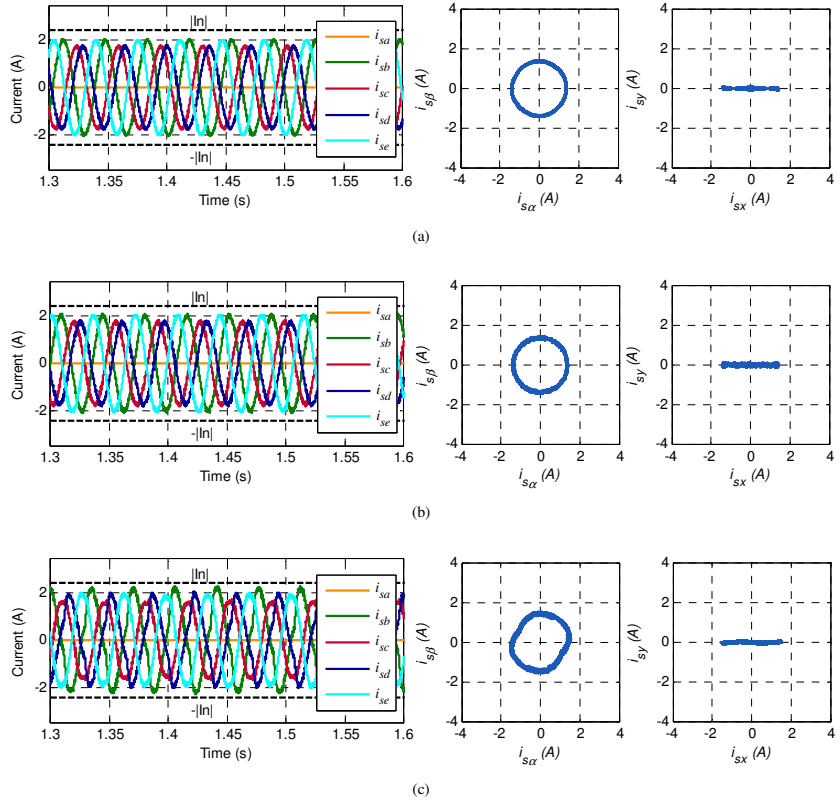


Fig. 9. Steady state operation. Stator phase currents (left hand side plots) and evolution in the α - β (middle plots) and x - y (right hand side plots) planes, with a reference speed of 500 rpm and a load torque of about 56% of the nominal one, implementing (a) PR, (b) PCC and (c) DTC controllers, respectively.

V. CONCLUSIONS

Multiphase motor drives have been recently used in applications where a high fault-tolerant capability is an important requirement of the system. The symmetrical five-phase induction motor drive is one interesting multiphase drive, and high performance controllers have been developed based on the RFOC method to take advantage of this fault-tolerant capability. DTC techniques have been also proposed in very recent times, but there is a lack of comparison studies of the closed-loop system performance using DTC and RFOC controllers when facing the open-phase fault situation. This paper presents this comparison analysis for the first time, showing that DTC controllers are a viable alternative to RFOC methods in symmetrical five-phase induction motor drive. Although the DTC technique generates slightly poorer system performance than using RFOC methods with PCC current controller, its simpler implementation can make DTC an interesting alternative in particular applications.

ACKNOWLEDGMENT

The authors would like to thank the Junta de Andalucía and the Ministerio de Economía y Competitividad of the Spanish Government for their funding of this research under references P11-TEP-7555, DPI2013-44278-R and ENE2014-52536-C2-1-R.

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