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ROBUSTNESS OF THE DIRECT TORQUE CONTROL OF DOUBLE STAR INDUCTION MOTOR IN FAULT CONDITION

AHMED AZIB[1], DJAMEL ZIANE[1], TOUFIK REKIOUA[1], ABDELMOUNAÏM TOUNZI[2]

Key words: Double star induction motor (DSIM), Direct torque control (DTC), Voltage source inverter (VSI).

In this paper, direct torque control (DTC) applied to a double star induction motor (DSIM) is studied when one or several phases are lost. To this aim, a general decoupled model of the induction machine fed by two three parallel voltage source inverters (VSI) with up to three open phases is given. Then, using a proposed control scheme, the pulsating of the torque is reduced and the drive performance improved without synthesizing a set of optimal current waveforms as the existing techniques do. Numerical simulations and experimental results are carried out to highlight the effectiveness of the proposed control scheme.

1. INTRODUCTION

Thanks to its well-known advantages in terms of simple construction, reliability, ruggedness and low cost, induction machine has found very wide use in industrial applications. Furthermore, for specific applications such as automotive, aerospace, military and nuclear, multiphase induction machines are more and more used as a substitute for traditional three-phase drives to ensure the required high reliability. Thus, multiphase drive system based on a multiphase induction machines supplied by a multiphase converter can lead to many advantages in terms of reduced current stress of the converter components, reduced torque ripple and rotor current harmonic content...etc. In addition, this kind of multiphase device can increase the reliability and be able to operate in degraded mode with acceptable torque ripple [1]. The most common multiphase induction machine is the double star induction motor (DSIM), which has two sets of three phases windings, spatially shifted by $\gamma = 30$ electrical degrees, while the rotor is of squirrel cage type [2, 3].

As for several machines, in the case of any open phase condition, the DSIM presents torque oscillations that can affect the drive performances. Degrees of freedom of the control are then used to minimize these oscillations based on a set of optimal current waveforms synthesized according to a given criterion [4–7]. The main goal of such control is to provide the best possible parameters of drive while remaining the simplest possible. Direct torque control (DTC) is one of the efficient and robust ones. Indeed, by controlling stator flux and electromagnetic torque through hysteresis comparators [8–10], it provides fast torque responses and is quite insensitive to machine parameter variations.

This paper introduces the implementation of the DTC to the DSIM, when one or several phases, up to 3, are lost. This control scheme, with open phases, achieves the closed-loop control of the motor stator flux and electromagnetic torque without using any current loop or shaft sensor, it uses a simple switching table to determine the most opportune inverter state to attain a desired output torque. In fact, it allows the elimination of the torque ripples by self changing currents in the machine, and avoiding complex calculations as the existing techniques do. Numerical simulations and experimental results are carried out to highlight the effectiveness of the proposed control scheme.

2. MODELING OF DSIM WITH PHASES OPEN

To study the DSIM in steady state and transient conditions, its model is developed by expressing the electrical and mechanical equations. The DSIM models with up to three open phases are given in [4, 6]. To highlight the methodology used, we develop deeply the case of one open phase S_{a1}. The other cases can be constructed easily from the developed formalism. To do this, we consider the following stator and rotor voltage equations:

$$[V_s]=[R_s][I_s]+\frac{\mathrm{d}}{\mathrm{d}t}\big[[L_{ss}][I_s]+[L_{sr}][I_r]\big], \tag{1}$$

$$[V_r]=[R_r][I_r]+\frac{\mathrm{d}}{\mathrm{d}t}\big[[L_{rr}][I_r]+[L_{rs}][I_s]\big]. \tag{2}$$

For all phases, the voltage and current vectors are:

$$\begin{cases} [V_s]=[v_{sa1} \quad v_{sb1} \quad v_{sc1} \quad v_{sa2} \quad v_{sb2} \quad v_{sc2}]^{\mathrm{T}} \\ [I_s]=[i_{sa1} \quad i_{sb1} \quad i_{sc1} \quad i_{sa2} \quad i_{sb2} \quad i_{sc2}]^{\mathrm{T}} \\ [V_r]=[0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^{\mathrm{T}} \\ [I_r]=[i_{ra1} \quad i_{rb1} \quad i_{rc1} \quad i_{ra2} \quad i_{rb2} \quad i_{rc2}]^{\mathrm{T}} \end{cases}, \tag{3}$$

with:

– V_s, V_r and I_s, I_r: the stator and rotor voltage and current vectors respectively;

– R_s, R_r, L_{ss} and L_{rr}: the stator and rotor resistance and self inductance matrices respectively, L_{sr} and L_{rs} are the stator-rotor mutual inductance matrices.

The applied space vector method as a mathematical tool for the analysis of the electric machines uses a complete set of equations, and can be represented in various systems of coordinates. Because of the DTC control scheme, which requires only information about the stator, the stationary coordinates system α-β (fixed to the stator) is required. In order to obtain a decoupled model, it is shown in [4] that the original model can be split into two decoupled subspaces, α-β subspace and z subspace. The transformation matrix in the α-β subspace is given by:

[1] Faculté de Technologie, Université de Bejaia, Laboratoire de Technologie Industrielle et de l'information (LTII), 06000 Bejaia, Algérie, E-mail: ahazib@gmail.com
[2] Laboratoire L2EP, Lille France, E-mail: mounaim.tounzi@univ-lille1.fr

$$\begin{bmatrix} i_{s\alpha 1} \\ i_{s\beta 1} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(0) & \cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{4\pi}{3}\right) \\ \sin(0) & \sin\left(\frac{2\pi}{3}\right) & \sin\left(\frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{sa1} \\ i_{sb1} \\ i_{sc1} \end{bmatrix}, \tag{4}$$

$$\begin{bmatrix} i_{s\alpha 2} \\ i_{s\beta 2} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\gamma) & \cos\left(\gamma+\frac{2\pi}{3}\right) & \cos\left(\gamma+\frac{4\pi}{3}\right) \\ \sin(\gamma) & \sin\left(\gamma+\frac{2\pi}{3}\right) & \sin\left(\gamma+\frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_{sa2} \\ i_{sb2} \\ i_{sc2} \end{bmatrix}. \tag{5}$$

We set from (4) and (5):

$$[\alpha_{01}] = \left[\cos(0) \quad \cos\left(\frac{2\pi}{3}\right) \quad \cos\left(\frac{4\pi}{3}\right) \right]$$

$$[\beta_{01}] = \left[\sin(0) \quad \sin\left(\frac{2\pi}{3}\right) \quad \sin\left(\frac{4\pi}{3}\right) \right]$$

$$[\alpha_{02}] = \left[\cos(\gamma) \quad \cos\left(\gamma+\frac{2\pi}{3}\right) \quad \cos\left(\gamma+\frac{4\pi}{3}\right) \right]$$

$$[\beta_{02}] = \left[\sin(\gamma) \quad \sin\left(\gamma+\frac{2\pi}{3}\right) \quad \sin\left(\gamma+\frac{4\pi}{3}\right) \right].$$

Thus, we can define $[\alpha_0]$ and $[\beta_0]$ such as:

$$[\alpha_0] = [\alpha_{01}, \alpha_{02}] \tag{6}$$

$$[\beta_0] = [\beta_{01}, \beta_{02}]. \tag{7}$$

Hence, the new matrix taking into consideration all the six phases of the DSIM can be written under the form:

$$[T_c] = \begin{bmatrix} [\alpha_0]/\|\alpha_0\| \\ [\beta_0]/\|\beta_0\| \end{bmatrix}, \tag{8}$$

where $\|\alpha_0\|$ and $\|\beta_0\|$ are the Euclidian norm of the vector $[\alpha_0]$ and $[\beta_0]$ respectively. Then the new matrix for the current is given by:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = [T_c][I_s]. \tag{9}$$

The z subspace is defined by N–2 orthogonal basis vectors (four vectors $[z_1]$, $[z_2]$, $[z_3]$ and $[z_4]$ for N=6 with N representing the number of active phases) and it has to be orthogonal to α-β subspace. On the other hand $[z_1]$, $[z_2]$, $[z_3]$ and $[z_4]$ give the basis of the null space of $[T_c]$.

$$[T_z] = \mathrm{null}[T_c]. \tag{10}$$

The matrix $[T_Z]$ with four vectors $[z_1]$, $[z_2]$, $[z_3]$ and $[z_4]$ can be easily obtained using the function "null" of matrix $[T_c]$ in MATLAB. Then, using (8) and (10) the transformation matrix $[T_N]$ is the following:

$$[T_N] = \begin{bmatrix} [T_c] \\ [T_z] \end{bmatrix}. \tag{11}$$

The matrix $[T_N]$ can provide the components of currents in α-β subspace and z subspace

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{sz} \end{bmatrix} = [T_N][i_s]. \tag{12}$$

When the phase s_{a1} is opened, the current and voltage vectors are:

$$\begin{cases} [V_s] = [v_{sb1} \quad v_{sc1} \quad v_{sa2} \quad v_{sb2} \quad v_{sc2}]^{\mathrm{T}} \\ [I_s] = [i_{sb1} \quad i_{sc1} \quad i_{sa2} \quad i_{sb2} \quad i_{sc2}]^{\mathrm{T}} \\ [V_r] = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^{\mathrm{T}} \\ [I_r] = [i_{ra1} \quad i_{rb1} \quad i_{rc1} \quad i_{ra2} \quad i_{rb2} \quad i_{rc2}]^{\mathrm{T}} \end{cases}. \tag{13}$$

The new model of DSIM with s_{a1} opened in α-β subspace can be given by:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = [T_{c1}][I_s], \text{ where } [T_{c1}] = \begin{bmatrix} [\alpha]/\|\alpha\| \\ [\beta]/\|\beta\| \end{bmatrix}. \tag{14}$$

$[\alpha]$ and $[\beta]$ are obtained by suppressing the components corresponding to open phase(s) in (6) and (7).

In z subspace the model of the DSIM with S_{a1} opened is defined by N–2 orthogonal basis vectors (three vectors $[z_1]$, $[z_2]$ and $[z_3]$ for $N = 5$ with N representing the number of active phases) and they are given by applying the function "null" in MATLAB :

$$[T_{z1}] = \mathrm{null}[T_{c1}]. \tag{15}$$

Using (14) and (15) the transformation matrix $[T_{N1}]$ is the following:

$$[T_{N1}] = \begin{bmatrix} [T_{c1}] \\ [T_{z1}] \end{bmatrix}. \tag{16}$$

The matrix $[T_{N1}]$ can provide the components of currents in α-β subspace and z subspace so:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{sz} \end{bmatrix} = [T_{N1}][i_s]. \tag{17}$$

2.1. EQUATION OF DSIM IN α-β SUBSPACE

From system (13), the decoupled model of the double star induction machine gives the equations of stator and rotor voltages:

$$\begin{cases} V_{s\alpha} = R_s i s_{s\alpha} + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_{s\alpha} \\ V_{s\beta} = R_s i s_{s\beta} + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_{s\beta} \end{cases}, \tag{18}$$

$$\begin{cases} 0 = R_r i_{r\alpha} + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_{r\alpha} + \omega_r \Phi_{r\beta} \\ 0 = R_r i_{r\beta} + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_{r\beta} - \omega_r \Phi_{r\alpha} \end{cases} \tag{19}$$

$\Phi_{s\alpha}$, $\Phi_{s\beta}$, $\Phi_{r\alpha}$ and $\Phi_{r\beta}$: are respectively the stator and rotor flux in space α-β

$$\begin{cases} \varphi_{s\alpha} = L_{sd} i_{s\alpha} + M_d i_{r\alpha} \\ \varphi_{s\beta} = L_{sq} i_{s\beta} + M_q i_{r\beta} \\ \varphi_{r\alpha} = L_r i_{r\alpha} + M_d i_{s\alpha} \\ \varphi_{r\beta} = L_r i_{r\beta} + M_q i_{s\beta} \end{cases}, \tag{20}$$

with:

$$\begin{cases} L_{sd} = L_{1s} + \|\alpha\|^2 L_{ms}, \quad M_d = \|\alpha_0\|.\|\alpha\|.L_{ms} \\ L_{sq} = L_{1s} + \|\beta\|^2 L_{ms} \qquad M_q = .\|\beta\|.\|\beta\|.L_{ms} \\ L_r = L_{1r} + \|\alpha_0\|^2 L_{ms} = L_{1r} + \|\beta_0\|^2 L_{ms} \end{cases},$$

where L_{ms}, L_{1s} and L_{1r}: are stator- rotor mutual inductance and stator, rotor leakage inductance respectively.

2.2. EQUATION OF DSIM IN (z) SUBSPACE

The DSIM in (z) subspace is described by the voltage equations as:

$$\begin{cases} V_{sz1} = R_s i_{sz1} + L_{1s} \dfrac{\mathrm{d}}{\mathrm{d}t} i_{sz1} \\ V_{sz2} = R_s i_{sz2} + L_{1s} \dfrac{\mathrm{d}}{\mathrm{d}t} i_{sz2} \\ V_{sz3} = R_s i_{sz3} + L_{1s} \dfrac{\mathrm{d}}{\mathrm{d}t} i_{sz3} \end{cases}. \tag{21}$$

The expression of the electromagnetic torque of DSIM is the following:

$$T_{em} = P\left(M_q i_{s\beta} i_{r\alpha} - M_d i_{s\alpha} i_{r\beta}\right). \tag{22}$$

3. **DIRECT TORQUE CONTRO OF DSIM WITH OPEN PHASES**

In this proposed control strategy, the control variables are the stator flux and electromagnetic torque which are obtained from only stator currents and dc-link voltage, that are used with the inverter switches states to estimate the value of the stator flux and electromagnetic torque without any use of mechanical sensor. So it is based on the same fundamentals and analysis of the drive as classical DTC without open phases [11, 12]. However the DTC with open phases needs to use the matrix $[T_N]$ transformation corresponding to open phases as determined previously to get new corresponding stator currents and then the estimation of the stator flux and electromagnetic torque. Regarding the knowledge of the machine parameters, the value of stator resistance is needed in order to calculate the flux.

3.1. FLUX ESTIMATION

The stator flux Φ_s can be estimated from the diphase stator quantities $I_{s\alpha,\beta}$ and $V_{s\alpha,\beta}$. The latter are obtained from the measurement of instantaneous stator currents and voltages and the application of the $[T_N]$ transformation so:

$$\begin{cases} \Phi_{s\alpha} = \displaystyle\int_0^t \left(V_{s\alpha} - R_s I_{s\alpha}\right)\mathrm{d}t \\ \Phi_{s\beta} = \displaystyle\int_0^t \left(V_{s\beta} - R_s I_{s\beta}\right)\mathrm{d}t \end{cases}. \tag{23}$$

Then, the stator flux module is written:

$$\Phi_s = \sqrt{\left(\Phi_{s\alpha}\right)^2 + \left(\Phi_{s\beta}\right)^2}. \tag{24}$$

The sector where the flux vector Φ_s is lying is determined from the components $\Phi_{s\alpha}$ and $\Phi_{s\beta}$. Thus, the angle θ_s is expressed by:

$$\theta_s = a\tan\left(\frac{\Phi_{s\beta}}{\Phi_{s\alpha}}\right). \tag{25}$$

3.2. TORQUE ESTIMATION

The electromagnetic torque can be estimated using only the magnitudes of the stator flux and current in the α-β subspace. Thus, the effectiveness of such control is the proper estimation of stator flux. The electromagnetic torque can get the form:

$$T_{em} = \frac{p}{L_r}\left(\phi_{r\alpha} i_{s\beta} M_q - \phi_{r\beta} i_{s\alpha} M_d\right). \tag{26}$$

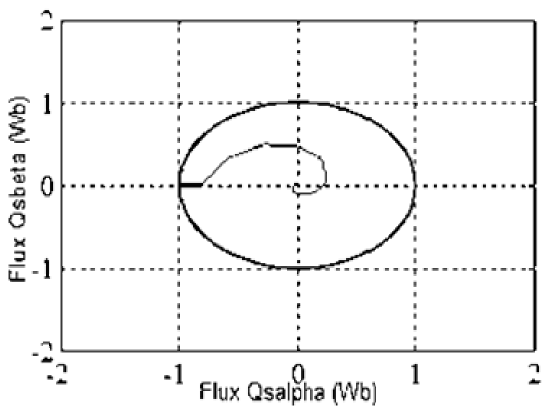
4. **SIMULATION AND EXPERIMENTAL RESULTS**

To verify the effectiveness of the proposed method, a study by numerical simulation of the dynamic behavior of DSIM controlled by the direct torque control with open phases from 1 to 3 phases open is achieved. The simulation parameters are: the reference flux: $\Phi^*_s = 1$ Wb and the reference torque for $0 \le t \le 1$ s $T^*_{em} = 7$ N.m, for $1 \le t \le 2$ s $T^*_{em} = -7$ N.m, the sampling period $T_{ech} = 10$ µs. Then a laboratory prototype is used with the proposed direct torque control under the same fault conditions (1 to 3 open phases). The experimental setup consists on a 4.5 kW double star induction motor with a squirrel cage rotor, a dc generator supplying a resistor as a load and two IGBT voltage source inverters. The control scheme for the DSIM was implemented by the dSPACE 1104 system based on the MPC8240 processor and TMS320F240 DSP processor.

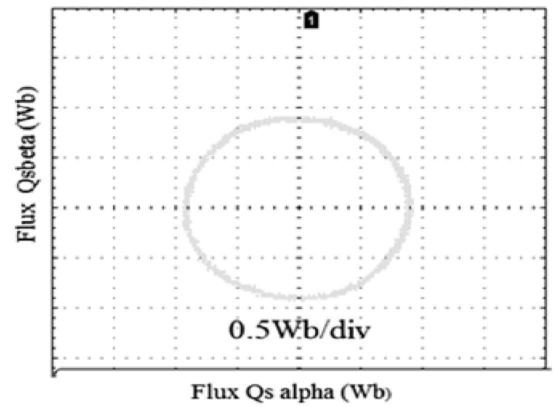
Figures 1a$_i$ to 4a$_i$ with ($i = 1, 2, 3$) show the simulation results of the DSIM using the proposed control algorithm for the 3 cases: Fig. 1: one phase (s_{a1}) lost; Fig. 2: two phases (s_{a1} and s_{b2}) lost and Fig. 4: three phases (s_{a1}, s_{b1} and s_{c1}) lost.

Figures 1a$_1$ and Fig. 2a$_1$ present the stator flux circular trajectory waveform. Whatever the studied case, the magnitude of the flux remains almost constant around the flux reference imposed of 1 Wb.

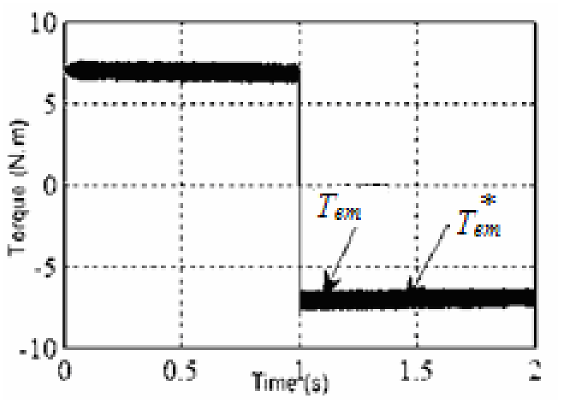
Figures 1a$_2$, 2a$_2$ and 4a$_1$ illustrate the simulation results of the time variation of the torque for the three studied cases. As it can be seen, the electromagnetic torque reaches its references in all cases.



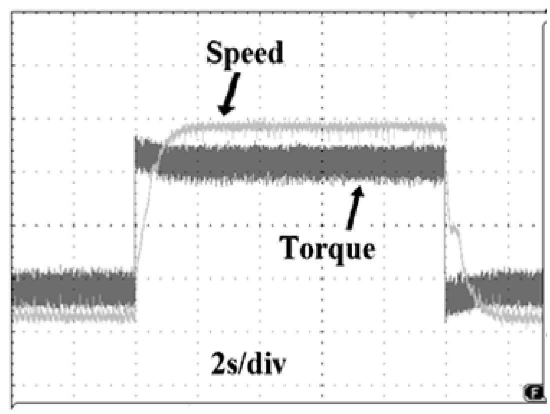
a$_1$) stator flux



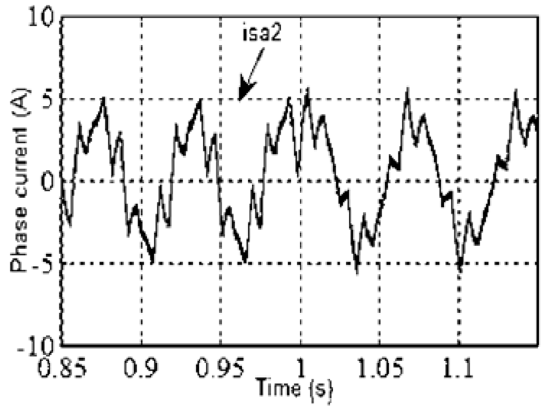
b$_1$) stator flux



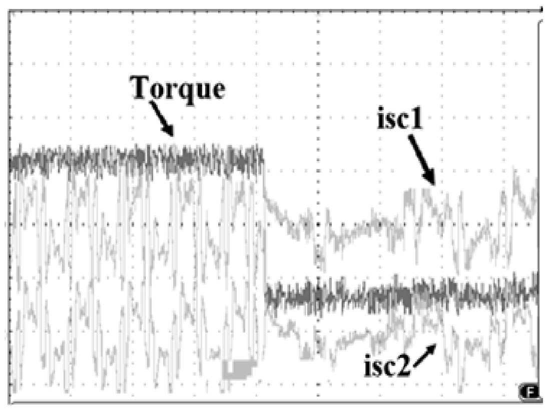
a$_2$) motor torque dynamic



b$_2$) motor torque and speed (5 N.m/div, 168 tr/min/div)



a$_3$) phase stator current

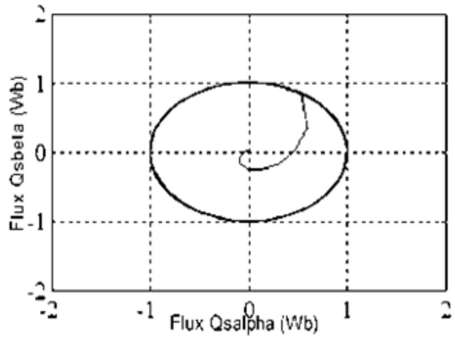


b$_3$) phases stator currents

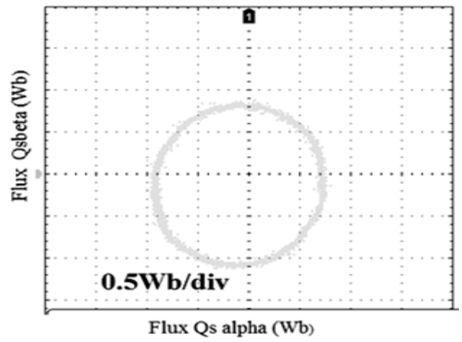
Fig. 1 – The performance of DSIM with S_{a1} open : a) simulation results; b) experimental results.

Figures 1a$_3$, Fig. 2a$_3$ and Fig. 4a$_2$ show the waveforms of the phases current for the different cases. The waveforms of the phase currents are not sinusoidal for the cases I: one phase (s_{a1}) is lost, II: two phases (s_{a1} and s_{b2}) are lost, because the existence of the components which do not contribute in the electromagnetic conversion energy is inevitable because of the inverter. Peaks of current of the circulating harmonics with important amplitude appear and deform the currents of phase. On the other hand in case III: three phases (s_{a1}, s_{b1} and s_{c1}) are lost, we disconnected three phases, it means one star is opening; the machine behaves as a three phase machine. Currents are not deformed because there are not circulating harmonics. Fig.1b$_i$ to 4b$_i$ with (i = 1, 2, 3) show various experimental waveforms for the proposed control scheme in the same condition as for the simulation. One can see the same waveforms for the simulations and the experiments.

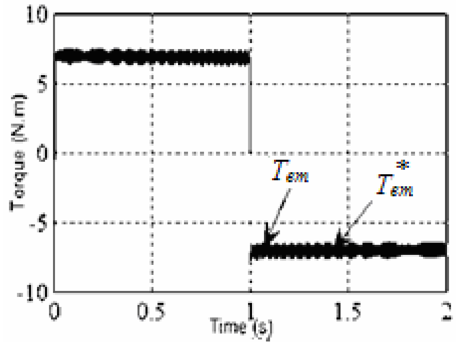
In Figs. 3a$_1$ and Fig. 3b$_1$, we studied the performance of the DSIM with transition from 5 phases active to 4 phases active. So at first the DSIM was fed by (s_{a2}, s_{b1}, s_{b2}, s_{c1} and s_{c2}) and then at t = 1 s we open s_{b2}, those figures represent simulation and experimental waveforms of the i_{sb2}, i_{sc2} respectively. As can be seen, for $t \geq 1$ s the i_{sb2} became zero and the current i_{sc2} magnitude is increased in order to maintain the same torque as when the DSIM operated with 5 phases.



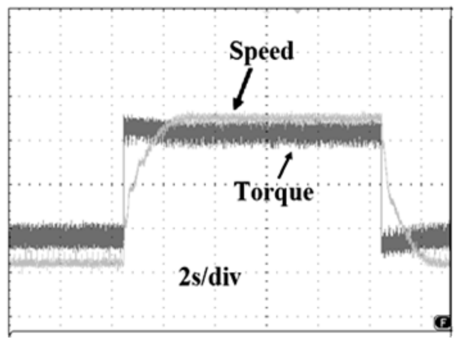
a$_1$) stator flux circular trajectory



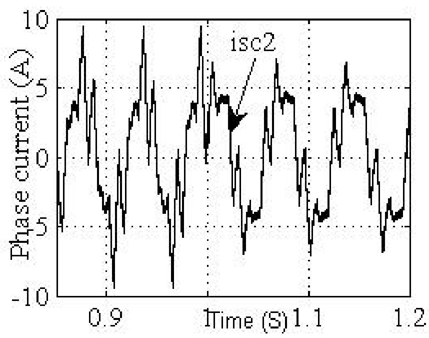
b$_1$) stator flux circular trajectory



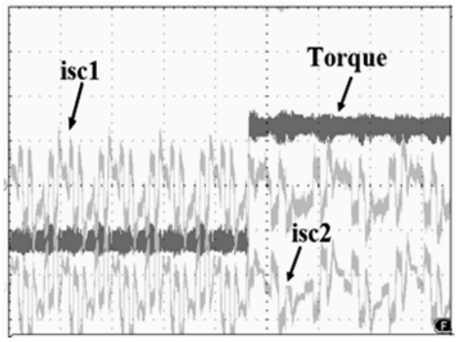
a$_2$) motor torque dynamic



b$_2$) motor torque and speed (5 N·m/div, 168 tr/min/div)

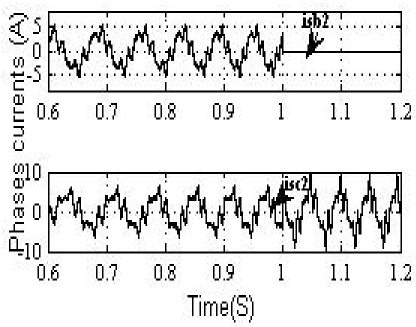


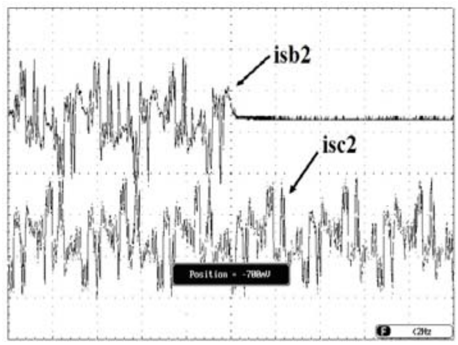
a$_3$) phase stator current



b$_3$) phases stator currents

Fig. 2 – The performance of DSIM with S_{a1} and S_{b2} open: a) simulation; b) experimental results.

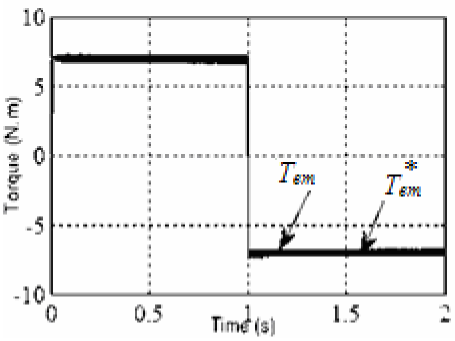




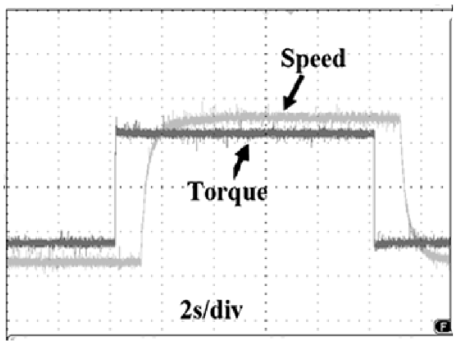
a$_1$) phases stator currents

b$_1$) phases stator currents

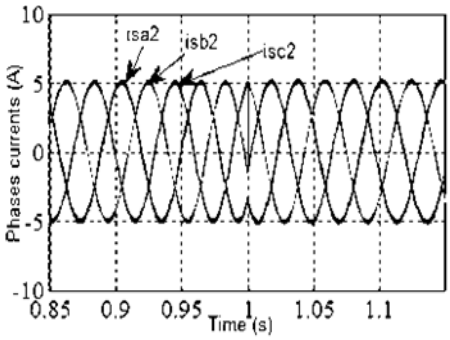
Fig. 3 – The performance of DSIM with transition from 5 phases active to 4 phases active stator currents. At t = 1 s we open is_{b2}: a) simulation; b) experimental results.



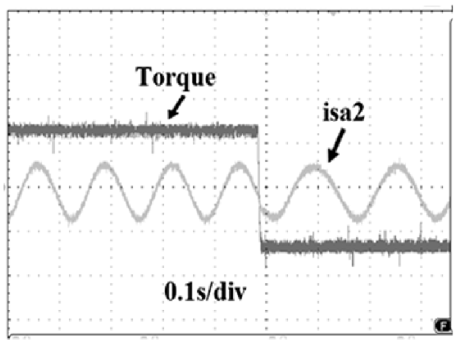
a$_1$) motor torque dynamic



b$_1$) motor torque and speed (5 N.m/div, 84 tr/min/div)



a$_2$) phases stator currents



b$_2$) phases stator currents

Fig. 4 – The performance of DSIM with S_{a1}, $S_{b1}$and S_{c1} open: a) simulation; b) experimental results.

5. **CONCLUSION**

In this work, a kind of degraded mode operation of direct torque control has been validated for a double star induction machine fed by parallel-connected dual voltage source inverters. The results have been obtained by following steps: first the machine was specially designed to take into account some properties, such as: the electromechanical energy conversion takes place only in α-β subspace, to minimize the variables of z subspace because they produce only losses and to allow possibility of analysis at any supply voltage waveform with open phase(s). This control strategy, ensures operation as satisfactory as possible by dramatically reducing the torque ripple. The numerical simulation and experimental results carried out, show the effectiveness of the proposed method in steady state and transient conditions, so it is possible to operate with this type of machine in the case of disconnection of one or more phases.

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