Modeling and Control of Six-Phase Symmetrical Induction Machine Under Fault Condition Due to Open Phases

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***Abstract*—This paper introduces a new fault-tolerant operation method for a symmetrical six-phase induction machine (6PIM) when one or several phases are lost. A general decoupled model of the induction machine with up to three open phases is given. This model illustrates the existence of a pulsating torque when phases are opened. Then, a new control method reducing the pulsating torque and the motor losses is proposed in order to improve the drive performances. The proposed method is compared to two other existing techniques. The simulation and experimental results obtained on a dedicated test-rig confirm the validity and the efficiency of the proposed method for a fault-tolerant symmetrical 6PIM drive.**

***Index Terms*—Fault tolerance, motion control, multiphase induction machines, torque control.**

NOMENCLATURE

$\|X\|$	Euclidian norm of vector X.
X^{T}	Transpose of vector X.
V	Instantaneous phase voltage vector.
I	Instantaneous phase current vector.
v	Instantaneous phase voltage.
i	Instantaneous phase current.
I_{m}	Rated rms phase current.
Ψ	Linkage flux.
γ	Phase-shift between two consecutive stator windings.
R	Resistance.
L	Inductance.
M	Mutual inductance.
P	Number of pole pairs.
J	Total shaft inertia.
F	Friction coefficient.
Ω	Rotor mechanical shaft speed.
ω_{s}	Stator MMF angular speed.
ω_{r}	Rotor electrical angular speed (P. Ω).
T_{m}	Electromagnetic torque.
T_{L}	Load torque.
τ_{r}	Equivalent rotor time constant ($\tau_{\mathrm{r}} = L_{\mathrm{r}}/R_{\mathrm{r}}$).
Subscripts	
$\alpha\beta z$	Stationary frame quantities.
$dq0$	Synchronous rotating frame quantities.
s	Stator quantities.
r	Rotor quantities.

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I. INTRODUCTION

FOR INDUSTRIAL applications such as automotive, aerospace, military and nuclear where high reliability is required, it is clear that multiphase induction machines are more and more used as a substitute for traditional three-phase drives. In the multiphase drive systems, the electrical machine has more than three phases on the stator side and the same number of legs is required for the inverter.

At the very beginning of their history, multiphase machines have been created to divide the total power by a number greater than three in order to overcome the limits of power semiconductors in the drive inverter or even in the machine phases for very high power rating. The first paper on a dynamic model of the six-phase induction machine (6PIM) was published in 1980 [1]. The other issue was related to harmonic elimination since it was not possible to apply special voltage patterns through the inverter for high power. A state of the art on multiphase machine design and the related space harmonics was published in the early 1980s [2], [3].

Nowadays, multiphase machines are even considered for small power in all applications requiring reliability and fault tolerance. In this way, it is expected that the loss of one or more phases allows the machine to provide a significant electromagnetic torque to run the system. On the other hand, the high performances of modern power converters in terms of switching frequency and control capability can be used to reduce torque oscillations in the case of phase loss.

Among the numerous possibilities of multiphase ac machines, the 6PIM is probably the most popular in industrial applications. The 6PIM is also known as the dual three-phase induction machine. Two winding arrangements are mainly used: the first one with 60 electrical degrees phase-shift in

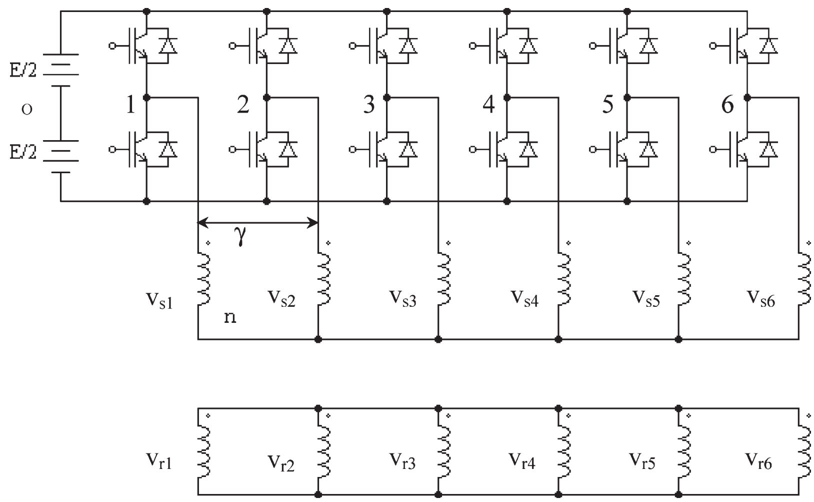

Fig. 1. 6PIM drive.

between two consecutive phases known as symmetrical 6PIM and the other one with 30 electrical degrees phase-shift in between two consecutive phases. It is clear that one way to deal with 6PIM drives is to extend control techniques used for three-phase induction machines in order to improve reliability and fault-tolerance [4], [5]. The other advantage is the increase of control degrees of freedom on the inverter for which the space vector decomposition is more complex than in the case of three phases [6]. For the dual-three phase induction machine, a unified approach to represent the model with one open phase has been presented with field-oriented control [7], [8]. One of the main problems is to obtain a general model suitable for both healthy and faulty conditions and some papers have been published on the subject [7]–[9].

In order to solve the problem of fault tolerance, it has been proposed to closely relate it to the control techniques used in the drive [10]–[14]. For stator winding faults, this problem has been treated in the same way for both synchronous and induction machines. The influence of the winding design and of the open phases on the stator current harmonics has been studied showing the importance of torque oscillations on the machine performances [15]. On the other hand, the influence of the control method on the 6PIM has been widely developed for both field-oriented and direct torque control methods [16]. Recently, new original applications for the control of multiphase induction machines have been presented [17], [18].

The purpose of this paper is to give a general model for the 6PIM under open phase fault. This model is more general than the ones published previously since it allows studying all possible cases up to three open phases. Then, the model is used to predict torque oscillations under faulty conditions such as open phases. The proposed method is based on the simple computation of the $\alpha\beta$ stator currents with two magnitudes related by an analytical condition obtained from the analysis of the electromagnetic torque when the machine is faulty. Indeed, the analysis shows that the electromagnetic torque oscillations are reduced with a particular magnitude ratio for the $\alpha\beta$ stator currents. This ratio depends only on the location of the open phase(s) whatever the machine parameters are. Moreover, the proposed technique minimizes also the machine losses in faulty conditions.

The proposed approach has been compared with two other methods. The first one [7], [8] consists of solving a system of algebraic equations in order to maintain a balanced sinusoidal rotating MMF. The solution of the system gives the current references that have to be set in the machine windings. The second method [10] is based on the modification of only one phase current in order to minimize the torque oscillation. The phase is chosen in such a way that the new currents compensate efficiently the loss of the faulted phase. Experimental results for one open phase will confirm the validity of the proposed technique.

II. 6PIM Model With Open Phases

The basic equations of 6PIM (Fig. 1) under balanced operating conditions are given in [6], [9], and [19]. In this paper, the 6PIM models with up to three open phases are given. In order to simplify the study, the case of one phase s1 open is under focus and the other cases will be built starting from this simple formulation. Whatever the open phases are, the stator and rotor voltage equations can be written as

$$[V_\mathrm{s}] = [R_\mathrm{s}]\cdot[I_\mathrm{s}] + \frac{d}{dt}\left([L_\mathrm{ss}]\cdot[I_\mathrm{s}] + [L_\mathrm{sr}]\cdot[I_\mathrm{r}]\right) \tag{1}$$

$$[V_\mathrm{r}] = [R_\mathrm{r}]\cdot[I_\mathrm{r}] + \frac{d}{dt}\left([L_\mathrm{rr}]\cdot[I_\mathrm{r}] + [L_\mathrm{rs}]\cdot[I_\mathrm{s}]\right). \tag{2}$$

When the phase s1 is opened, the current and voltage vectors are

$$\begin{cases} [V_\mathrm{s}] = [\,v_\mathrm{s2} \quad v_\mathrm{s3} \quad v_\mathrm{s4} \quad v_\mathrm{s5} \quad v_\mathrm{s6}]^\mathrm{T} \\ [I_\mathrm{s}] = [\,i_\mathrm{s2} \quad i_\mathrm{s3} \quad i_\mathrm{s4} \quad i_\mathrm{s5} \quad i_\mathrm{s6}]^\mathrm{T} \\ [V_\mathrm{r}] = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^\mathrm{T} \\ [I_\mathrm{r}] = [\,i_\mathrm{r1} \quad i_\mathrm{r2} \quad i_\mathrm{r3} \quad i_\mathrm{r4} \quad i_\mathrm{r5} \quad i_\mathrm{r6}\,]^\mathrm{T}. \end{cases} \tag{3}$$

In these equations, $[R_\mathrm{s}]$, $[R_\mathrm{r}]$, $[L_\mathrm{ss}]$, $[L_\mathrm{rr}]$, $[L_\mathrm{sr}]$, and $[L_\mathrm{rs}]$ are matrices including the model parameters described in [19]. The drawback of this model lies in the coupled nonlinear expressions of the inductance matrices. In order to obtain a decoupled model, it is shown in [6] that two transformation matrices are required. These matrices, so-called [T5] and [T6], split the original model into two decoupled subspaces: $\alpha\beta$-subspace and z-subspace. The first one represents the electromechanical energy conversion subspace while the other one gives only losses. The transformation matrix decomposing the model given by the (1) and (2) into $\alpha\beta$-subspace and z-subspace will be presented. The electromechanical energy conversion takes place only in $\alpha\beta$-subspace which means that the MMF produced by five stator phases is equivalent to the MMF produced by two windings on the axes α and β with the currents $i_{\mathrm{s}\alpha}$ and $i_{\mathrm{s}\beta}$, respectively. These currents are defined by

$$\begin{bmatrix} i_{\mathrm{s}\alpha} \\ i_{\mathrm{s}\beta} \end{bmatrix} = [T_{\mathrm{c}}][I_{\mathrm{s}}], \qquad \text{where } [T_{\mathrm{c}}] = \begin{bmatrix} [\alpha]/\|\alpha\| \\ [\beta]/\|\beta\| \end{bmatrix} \tag{4}$$

$[\alpha]$ and $[\beta]$ are obtained by suppressing the components corresponding to the open phase(s) in (5a) and (5b), which is shown at the bottom of the next page [17].

φ_i, $i = 1$ to 6 are the stator current phase angles defined as: $\varphi_1 = 0$, $\varphi_2 = \gamma$, $\varphi_3 = 2\pi/3$, $\varphi_4 = 2\pi/3 + \gamma$, $\varphi_5 = 4\pi/3$, $\varphi_6 = 4\pi/3 + \gamma$. φ_0 is fixed to obtain two orthogonal vectors $[\alpha]$ and $[\beta]$

$$\varphi_0 = \frac{-1}{2}\tan^{-1}\left(\frac{\sum_j \sin(2\varphi_j)}{\sum_j \cos(2\varphi_j)}\right) \tag{6}$$

for all j belonging to the set of active phases.

For example, when s1 is opened ($j = 2$ to 6) and $\gamma = 60^\circ$, the (6) gives $\varphi_0 = 0$ and then, $[\alpha]$ and $[\beta]$ become (7a) and (7b), which is shown at the bottom of the next page.

These vectors determine the matrix $[T_{\mathrm{c}}]$ in accordance with (4). It should be noted that $\|\alpha\|^2 + \|\beta\|^2 = N$ where N is the number of active phases ($2 \leq N \leq 6$).

The z-subspace is defined by N$-$2 orthonormal basis vectors (three vectors $[z1]$, $[z2]$ and $[z3]$ for $N = 5$) and it has to be orthogonal to $\alpha\beta$-subspace [2]. On the other hand, $[z1]$-$[z2]$-$[z3]$ give the basis of the null space of $[T_{\mathrm{c}}]$

$$[T_z] = \mathrm{null}\left([T_{\mathrm{c}}]\right)^{\mathrm{T}} = \begin{bmatrix} [z1]/\|z1\| \\ [z2]/\|z2\| \\ [z3]/\|z3\| \end{bmatrix}. \tag{8}$$

The matrix $[T_z]$ can be easily obtained using "null" function in MATLAB. Then, using (4) and (8), the transformation matrix $[T_N]$ ($2 \leq N \leq 6$) is the following:

$$[T_N] = \begin{bmatrix} [T_{\mathrm{c}}] \\ [T_z] \end{bmatrix}. \tag{9}$$

This matrix gives the stator current components in $\alpha\beta$-subspace and z-subspace

$$\begin{bmatrix} i_{\mathrm{s}\alpha\beta} \\ i_{\mathrm{sz}} \end{bmatrix} = [T_N][I_{\mathrm{s}}] \tag{10}$$

$i_{\mathrm{s}\alpha\beta}$ is used to control the electromechanical energy conversion while i_{sz} should be set to zero to minimize the losses.

When s1 is opened and $\gamma = 60^\circ$, the matrices [T5] and [T6] are

$$[\mathrm{T5}] = \begin{bmatrix} 0.5000 & -0.5000 & -1.0000 & -0.5000 & 0.5000 \\ 0.8660 & 0.8660 & 0.0000 & -0.8660 & -0.8660 \\ 0.5704 & -0.4102 & 0.6602 & -0.0898 & 0.2500 \\ 0.5469 & 0.2265 & -0.2265 & 0.7735 & -0.0000 \\ -0.0235 & 0.6367 & 0.1133 & -0.1367 & 0.7500 \end{bmatrix} \tag{11}$$

$$[\mathrm{T6}] = \begin{bmatrix} 1.000 & 0.500 & -0.500 & -1.000 & -0.500 & 0.500 \\ 0 & 0.866 & 0.866 & 0.000 & -0.866 & -0.866 \\ 0.384 & -0.42 & 0.762 & -0.140 & 0.096 & 0.237 \\ 0.577 & 0.105 & -0.105 & 0.788 & -0.105 & 0.105 \\ 0.192 & 0.535 & 0.131 & -0.070 & 0.798 & -0.131 \\ -0.384 & 0.4296 & 0.237 & 0.140 & -0.096 & 0.762 \end{bmatrix}. \tag{12}$$

By applying the transformation matrices [T5] and [T6] to the (1) and (2), the following formulation is obtained:

$$\begin{cases} [\mathrm{T5}]\cdot[V_{\mathrm{s}}] = [\mathrm{T5}]\cdot[R_{\mathrm{s}}]\cdot[\mathrm{T5}]^{-1}\cdot[\mathrm{T5}]\cdot[I_{\mathrm{s}}] + \frac{d}{dt}\big([\mathrm{T5}]\cdot[L_{\mathrm{ss}}] \\ \qquad \cdot[\mathrm{T5}]^{-1}\cdot[\mathrm{T5}]\cdot[I_{\mathrm{s}}] + [\mathrm{T5}]\cdot[L_{\mathrm{sr}}]\cdot[\mathrm{T6}]^{-1}\cdot[\mathrm{T6}]\cdot[I_{\mathrm{r}}]\big) \\ [\mathrm{T6}]\cdot[V_{\mathrm{r}}] = [\mathrm{T6}]\cdot[R_{\mathrm{r}}]\cdot[\mathrm{T6}]^{-1}\cdot[\mathrm{T6}]\cdot[I_{\mathrm{r}}] + \frac{d}{dt}\big([\mathrm{T6}]\cdot[L_{\mathrm{rr}}] \\ \qquad \cdot[\mathrm{T6}]^{-1}\cdot[\mathrm{T6}]\cdot[I_{\mathrm{r}}] + [\mathrm{T6}]\cdot[L_{\mathrm{rs}}]\cdot[\mathrm{T5}]^{-1}\cdot[\mathrm{T5}]\cdot[I_{\mathrm{s}}]\big). \end{cases} \tag{13}$$

It should be noted that if there are several open phases, all the corresponding components in $[\alpha_0]$ and $[\beta_0]$ have to be eliminated to obtain $[\alpha]$ and $[\beta]$. In this case, the transformed stator voltage and current vectors present the same number of variables as the number of active phases ($2 \leq N \leq 6$). When $N = 2$, there will be no z-component and $[\mathrm{T2}] = [T_{\mathrm{c}}]$, $[\mathrm{T2}][I_{\mathrm{s}}] = [i_{\mathrm{s}\alpha}\ i_{\mathrm{s}\beta}]^{\mathrm{T}}$ and $[\mathrm{T2}][V_{\mathrm{s}}] = [v_{\mathrm{s}\alpha}\ v_{\mathrm{s}\beta}]^{\mathrm{T}}$.

For s1 open and $\gamma = 60^\circ$, the 6PIM model in the two subspaces can be defined. Furthermore, any interested reader can download the program for matrix computation from [20].

A. Equations in $\alpha\beta$-Subspace

From (13), the decoupled 6PIM model gives the stator and rotor voltage equations

$$\begin{cases} v_{\mathrm{s}\alpha} = R_{\mathrm{s}}\cdot i_{\mathrm{s}\alpha} + \frac{d}{dt}\psi_{\mathrm{s}\alpha} \\ v_{\mathrm{s}\beta} = R_{\mathrm{s}}\cdot i_{\mathrm{s}\beta} + \frac{d}{dt}\psi_{\mathrm{s}\beta} \end{cases} \tag{14}$$

$$\begin{cases} 0 = R_{\mathrm{r}}\cdot i_{\mathrm{r}\alpha} + \frac{d}{dt}\psi_{\mathrm{r}\alpha} + \omega_{\mathrm{r}}\cdot\psi_{\mathrm{r}\beta} \\ 0 = R_{\mathrm{r}}\cdot i_{\mathrm{r}\beta} + \frac{d}{dt}\psi_{\mathrm{r}\beta} - \omega_{\mathrm{r}}\cdot\psi_{\mathrm{r}\alpha}. \end{cases} \tag{15}$$

$\Psi_{\mathrm{s}\alpha}$, $\Psi_{\mathrm{s}\beta}$, $\Psi_{\mathrm{r}\alpha}$ and $\Psi_{\mathrm{r}\beta}$ are, respectively $\alpha\beta$ components of the stator and rotor flux described as

$$\begin{cases} \psi_{\mathrm{s}\alpha} = L_{\mathrm{sd}} i_{\mathrm{s}\alpha} + M_d i_{\mathrm{r}\alpha} \\ \psi_{\mathrm{s}\beta} = L_{\mathrm{sq}} i_{\mathrm{s}\beta} + M_q i_{\mathrm{r}\beta} \end{cases} \tag{16}$$

$$\begin{cases} \psi_{\mathrm{r}\alpha} = M_d i_{\mathrm{s}\alpha} + L_{\mathrm{r}} i_{\mathrm{r}\alpha} \\ \psi_{\mathrm{r}\beta} = M_q i_{\mathrm{s}\beta} + L_{\mathrm{r}} i_{\mathrm{r}\beta}. \end{cases} \tag{17}$$

The other parameters are the following:

$$\begin{cases} L_{\mathrm{sd}} = L_{\mathrm{ls}} + \|\alpha\|^2 L_{\mathrm{ms}}, & M_d = \|\alpha_0\| \cdot \|\alpha\| \cdot L_{\mathrm{ms}} \\ L_{\mathrm{sq}} = L_{\mathrm{ls}} + \|\beta\|^2 L_{\mathrm{ms}}, & M_q = \|\beta_0\| \cdot \|\beta\| \cdot L_{\mathrm{ms}} \\ L_{\mathrm{r}} \ = L_{\mathrm{lr}} + \|\alpha_0\|^2 L_{\mathrm{ms}} = L_{\mathrm{lr}} + \|\beta_0\|^2 L_{\mathrm{ms}} \end{cases} \tag{18}$$

where $\|\alpha_0\| = \|\beta_0\| = \sqrt{3}$.

B. Equations in z-Subspace

The stator voltage equations are

$$\begin{cases} v_{\mathrm{sz1}} = R_{\mathrm{s}} \cdot i_{\mathrm{sz1}} + L_{\mathrm{ls}} \frac{di_{\mathrm{sz1}}}{dt} \\ v_{\mathrm{sz2}} = R_{\mathrm{s}} \cdot i_{\mathrm{sz2}} + L_{\mathrm{ls}} \frac{di_{\mathrm{sz2}}}{dt} \\ v_{\mathrm{sz3}} = R_{\mathrm{s}} \cdot i_{\mathrm{sz3}} + L_{\mathrm{ls}} \frac{di_{\mathrm{sz3}}}{dt}. \end{cases} \tag{19}$$

As can be concluded from (14), (15), and (19), the z-subspace is only related to the losses. Therefore, a suitable control strategy is required to minimize the z1-z2-z3 currents. From (19), the only parameters of the 6PIM model in z-subspace are R_{s} and L_{ls} and they are independent of the transformation matrix [T5] or even $[T_N]$ in the general case where N is the number of active phases. This is not true for the parameters of the $\alpha\beta-$subspace given in (14) and (15). In this case, Table I gives L_{sd}, L_{sq}, M_d and M_q for all cases up to three open phases ($N = 5,\ 4$ and 3). It can be noticed that the 6PIM model in $\alpha\beta-$subspace is always the same as shown in (14)–(18) whatever the open phases are.

The expression of the electromagnetic torque for a 6PIM is the following [12]:

$$T_{\mathrm{m}} = \frac{P}{L_{\mathrm{r}}}(M_q \cdot i_{\mathrm{s}\beta} \cdot \psi_{\mathrm{r}\alpha} - M_d \cdot i_{\mathrm{s}\alpha} \cdot \psi_{\mathrm{r}\beta}). \tag{20}$$

III. Electromagnetic Torque Computation

It is well known that the electromagnetic torque oscillates under an open phase fault. In this section, the electromagnetic torque is computed at steady state when the 6PIM is faulty and the $\alpha\beta$ stator currents are sinusoidal. In accordance with (20), it is necessary to obtain the rotor flux expression coming from (15), (16), and (17)

$$\begin{cases} \frac{d\psi_{\mathrm{r}\alpha}}{dt} = \frac{M_d}{\tau_{\mathrm{r}}} i_{\mathrm{s}\alpha} - \frac{1}{\tau_{\mathrm{r}}}\psi_{\mathrm{r}\alpha} - \omega_{\mathrm{r}} \cdot \psi_{\mathrm{r}\beta} \\ \frac{d\psi_{\mathrm{r}\beta}}{dt} = \frac{M_q}{\tau_{\mathrm{r}}} i_{\mathrm{s}\beta} - \frac{1}{\tau_{\mathrm{r}}}\psi_{\mathrm{r}\beta} + \omega_{\mathrm{r}} \cdot \psi_{\mathrm{r}\alpha}. \end{cases} \tag{21}$$

In order to obtain the sinusoidal steady state response of (21), it is necessary to set

$$\omega_{\mathrm{r}} = P \cdot \Omega \tag{22}$$

$$i_{\mathrm{s}\alpha}(t) = I_\alpha \cdot \sin(\theta_{\mathrm{s}}) \tag{23}$$

$$i_{\mathrm{s}\beta}(t) = I_\beta \cdot \sin(\theta_{\mathrm{s}} - \pi/2) \tag{24}$$

where I_α and I_β are constant and $\theta_{\mathrm{s}} = \omega_{\mathrm{s}} t$.

Here, ω_{r} is supposed to be constant even in the case of open phase(s) for which the rotor angular speed oscillates. However, the oscillation magnitude of the rotor speed is much lower than the one of the torque because of the natural filtering performed by the mechanical part. The assumption of a constant ω_{r} can be considered as a first approximation in order to linearize the model (21) around its operating point.

Substituting $i_{\mathrm{s}\alpha}$ and $i_{\mathrm{s}\beta}$ in (21) by their expressions given in (23) and (24), the sinusoidal steady state expressions of $\Psi_{\mathrm{r}\alpha}$ and $\Psi_{\mathrm{r}\beta}$ are obtained

$$\begin{cases} \psi_{\mathrm{r}\alpha} = \frac{1}{D}[\tau_{\mathrm{r}} \cdot \omega_{\mathrm{r}} \cdot M_q \cdot I_\beta \cdot \cos(\theta_{\mathrm{s}} - \phi_1) \\ \qquad + \sqrt{1 + \tau_{\mathrm{r}}^2 \cdot \omega_{\mathrm{s}}^2} M_d \cdot I_\alpha \cdot \sin(\theta_{\mathrm{s}} - \phi_1 + \phi_2)] \\ \psi_{\mathrm{r}\beta} = \frac{1}{D}[\tau_{\mathrm{r}} \cdot \omega_{\mathrm{r}} \cdot M_d \cdot I_\alpha \cdot \sin(\theta_{\mathrm{s}} - \phi_1) \\ \qquad - \sqrt{1 + \tau_{\mathrm{r}}^2 \cdot \omega_{\mathrm{s}}^2} \cdot M_q \cdot I_\beta \cdot \cos(\theta_{\mathrm{s}} - \phi_1 + \phi_2)] \end{cases} \tag{25}$$

with: $D = \sqrt{[1 + \tau_{\mathrm{r}}^2 \cdot (\omega_{\mathrm{r}}^2 - \omega_{\mathrm{s}}^2)]^2 + 4\tau_{\mathrm{r}}^2 \cdot \omega_{\mathrm{s}}^2}$, $\phi_2 = \tan^{-1}(\tau_{\mathrm{r}}\omega_{\mathrm{s}})$ and $\phi_1 = \tan^{-1}((2 \cdot \tau_{\mathrm{r}} \cdot \omega_{\mathrm{s}})/(1 + \tau_{\mathrm{r}}^2 \cdot (\omega_{\mathrm{r}}^2 - \omega_{\mathrm{s}}^2)))$. Then, the electromagnetic torque becomes

$$T_{\mathrm{m}} = \frac{P}{L_{\mathrm{r}}} \cdot (M_q \cdot i_{\mathrm{s}\beta} \cdot \psi_{\mathrm{r}\alpha} - M_d \cdot i_{\mathrm{s}\alpha} \cdot \psi_{\mathrm{r}\beta}) = \overline{T}_{\mathrm{m}} + \widetilde{T}_{\mathrm{m}} \tag{26}$$

$$\overline{T}_{\mathrm{m}} = \frac{P}{L_{\mathrm{r}}} \frac{1}{D} \Big[M_d \cdot M_q \cdot I_\alpha \cdot I_\beta \cdot \sqrt{1 + \tau_{\mathrm{r}}^2 \cdot \omega_{\mathrm{s}}^2} \cdot \sin(\phi_1 - \phi_2) - \frac{\tau_{\mathrm{r}} \cdot \omega_{\mathrm{r}}}{2} \left(M_d^2 \cdot I_\alpha^2 + M_q^2 \cdot I_\beta^2 \right) \cdot \cos(\phi_1) \Big] \tag{27}$$

$$\widetilde{T}_{\mathrm{m}} = \frac{P}{L_{\mathrm{r}}} \frac{\tau_{\mathrm{r}} \cdot \omega_{\mathrm{r}}}{2D} \left(M_d^2 \cdot I_\alpha^2 - M_q^2 \cdot I_\beta^2 \right) \cdot \cos(2\theta_{\mathrm{s}} - \phi_1). \tag{28}$$

Equation (26) shows clearly that the electromagnetic torque can be decomposed into a constant part $\overline{T}_{\mathrm{m}}$ and an oscillatory component $\widetilde{T}_{\mathrm{m}}$. The oscillation frequency is twice the power supply frequency as expected. The reduction of the torque oscillations can be achieved using a particular control of the $\alpha\beta$ stator currents.

$$[\alpha_0] = [\cos(\varphi_0 + \varphi_1) \quad \cos(\varphi_0 + \varphi_2) \quad \cos(\varphi_0 + \varphi_3) \quad \cos(\varphi_0 + \varphi_4) \quad \cos(\varphi_0 + \varphi_5) \quad \cos(\varphi_0 + \varphi_6)]^{\mathrm{T}} \tag{5a}$$

$$[\beta_0] = [\sin(\varphi_0 + \varphi_1) \quad \sin(\varphi_0 + \varphi_2) \quad \sin(\varphi_0 + \varphi_3) \quad \sin(\varphi_0 + \varphi_4) \quad \sin(\varphi_0 + \varphi_5) \quad \sin(\varphi_0 + \varphi_6)]^{\mathrm{T}} \tag{5b}$$

$$[\alpha] = [\cos(\gamma) \quad \cos(2\pi/3) \quad \cos(\gamma + 2\pi/3) \quad \cos(4\pi/3) \quad \cos(\gamma + 4\pi/3)]^{\mathrm{T}} \tag{7a}$$

$$[\beta] = [\sin(\gamma) \quad \sin(2\pi/3) \quad \sin(\gamma + 2\pi/3) \quad \sin(4\pi/3) \quad \sin(\gamma + 4\pi/3)]^{\mathrm{T}} \tag{7b}$$

TABLE I
MACHINE INDUCTANCES WITH OPEN PHASE(S) FOR $\gamma = 60°$

Open phase(s)	L_{sd}	L_{sq}	M_d	M_q
1 ; 4	L_{ls}+2L_{ms}	L_{ls}+3L_{ms}	2.449L_{ms}	3L_{ms}
2 ; 3 ; 5 ; 6	L_{ls}+3L_{ms}	L_{ls}+2L_{ms}	3L_{ms}	2.449L_{ms}
(1,2) ; (1,3) ; (1,5) ; (1,6) (2,4) ; (3,4) ; (4,5) ; (4,6)	L_{ls}+1.5L_{ms}	L_{ls}+2.5L_{ms}	2.121L_{ms}	2.739L_{ms}
(1,4)	L_{ls}+L_{ms}	L_{ls}+3L_{ms}	1.7321L_{ms}	3L_{ms}
(2,3) ; (2,6) ; (3,5) ; (5,6)	L_{ls}+2.5L_{ms}	L_{ls}+1.5L_{ms}	2.739L_{ms}	2.121L_{ms}
(2,5) ; (3,6)	L_{ls}+3L_{ms}	L_{ls}+1L_{ms}	3L_{ms}	1.732L_{ms}
(1,2,3) ; (1,2,6) ; (2,3,4) ; (3,4,5) ; (4,5,6) ; (1,3,5) ; (1,5,6) ; (2,4,6)	L_{ls}+1.5L_{ms}	L_{ls}+1.5L_{ms}	2.121L_{ms}	2.121L_{ms}
(1,2,4) ; (1,2,5) ; (1,3,4) ; (3,4,6) ; (1,3,6) ; (1,4,5) ; (1,4,6) ; (2,4,5)	L_{ls}+0.634L_{ms}	L_{ls}+2.366L_{ms}	1.3791L_{ms}	2.6642L_{ms}
(2,3,5) ; (2,3,6) ; (2,5,6) ; (3,5,6)	L_{ls}+2.366L_{ms}	L_{ls}+0.634L_{ms}	2.6642L_{ms}	1.3791L_{ms}

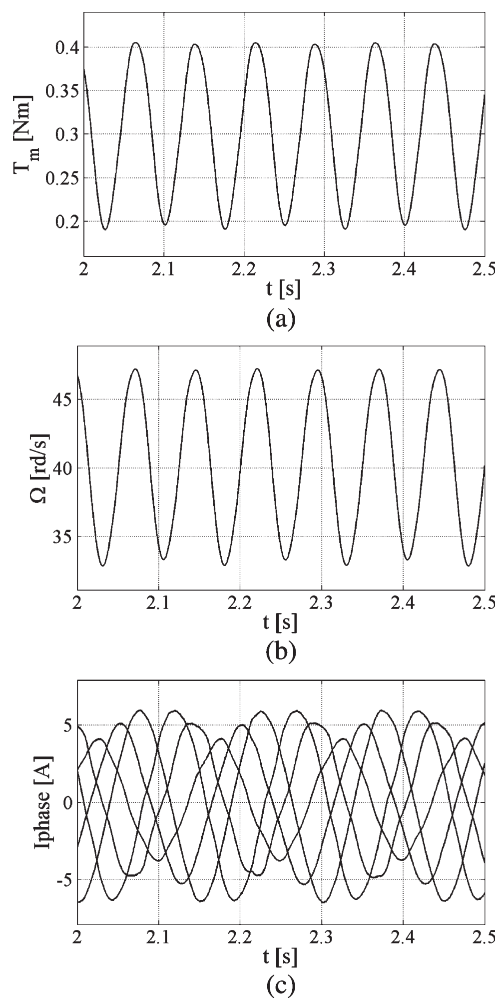

Fig. 2. Simulation results for s1 open without any compensation: (a) Estimated torque, (b) rotor speed, and (c) stator currents.

In order to predict the 6PIM behavior under open phase condition, a simulation program using MATLAB/Simulink software has been developed. The 6PIM model implemented is based on (14)–(20). Fig. 2 depicts, respectively, the motor torque, the rotor speed and the five stator currents in steady state when one phase is opened and without any compensation to reduce torque oscillations. The drive parameters are given in Table II (Section V).

It can be seen (Fig. 2) that the oscillations appear in both electromagnetic torque and rotor speed. The frequency of these oscillations is twice that of the stator currents ($\omega_s = 42$ rad/s) as shown in (26). According to (28), the magnitude of the torque oscillations is proportional to $M_d^2 I_\alpha^2 - M_q^2 I_\beta^2$. Therefore, the condition of existence of steady state pulsating torque is

$$M_d^2 I_\alpha^2 \neq M_q^2 I_\beta^2. \tag{29}$$

TABLE II
INDUCTION MACHINE PARAMETERS

Rated power	90 W
Rated torque	0.3 Nm
VSI DC bus voltage	42 V
Number of poles	2
Mutual inductance	30.9 mH
Stator resistance	1.04 Ω
Stator leakage inductance	0.30 mH
Rotor resistance	0.64 Ω
Rotor leakage inductance	0.65 mH
Friction coefficient	4×10^{-4} kg.m²/s
Inertia	9.5×10^{-5} kg.m²

Thus, in order to eliminate the torque oscillations, the following condition has to be imposed:

$$\left|\frac{I_\alpha}{I_\beta}\right| = \frac{M_q}{M_d} = \frac{\|\beta\|}{\|\alpha\|}. \tag{30}$$

It means that if the $\alpha\beta$ current magnitude ratio is fixed as given by (30), the electromagnetic torque presents no more oscillations and is reduced to its mean value given by the expression (27). It should be noted that this ratio depends only on the Euclidian norms of vectors $[\alpha]$ and $[\beta]$. For more than one open phase, the ratio can be obtained using Table I. For some cases, $M_d = M_q$ and according to expression (30) this will lead to a balance of the $\alpha\beta$ current pair. This is the main idea for reducing the torque oscillation in this paper, which will be described in Section IV-C.

IV. REDUCTION OF TORQUE OSCILLATIONS

As shown before, in any open phase condition, the 6PIM presents torque oscillations that can affect the drive performances. The aim is to take benefit of the drive control degree of freedom in order to minimize these oscillations. All the torque compensation methods are based on synthesizing a set of optimal current waveforms according to a given criterion.

Then, the set of stator currents is imposed by a voltage source inverter (VSI) to the 6PIM stator windings. The first method (method 1), presented in the following, gives a set of stator current references in order to obtain a sinusoidal MMF. The objective of the second method (method 2) is to change only one phase current to minimize the torque oscillations. Finally, the proposed method gives a set of $\alpha\beta$ current references which satisfies the expression (30) in any open phase case and which allows to reduce both torque oscillations and losses.

A. Method 1

According to the method described in [7], when one phase is opened, a disturbance-free rotating MMF can be generated by a new combination of phase currents. After opening the first phase s1, the remaining phase currents give a sinusoidal rotating MMF if the following conditions are satisfied:

$$\begin{aligned} & i_{\mathrm{s2}} \cdot \cos(\gamma) + i_{\mathrm{s3}} \cdot \cos(2\pi/3) + i_{\mathrm{s4}} \cdot \cos(2\pi/3+\gamma) \\ & \quad + i_{\mathrm{s5}} \cdot \cos(4\pi/3) + i_{\mathrm{s6}} \cdot \cos(4\pi/3+\gamma) = 3 \cdot I_{\mathrm{m}} \cdot \cos\theta_{\mathrm{s}} \end{aligned} \tag{31a}$$

$$\begin{aligned} & i_{\mathrm{s2}} \cdot \sin(\gamma) + i_{\mathrm{s3}} \cdot \sin(2\pi/3) + i_{\mathrm{s4}} \cdot \sin(2\pi/3+\gamma) \\ & \quad + i_{\mathrm{s5}} \cdot \sin(4\pi/3) + i_{\mathrm{s6}} \cdot \sin(4\pi/3+\gamma) = 3 \cdot I_{\mathrm{m}} \cdot \sin\theta_{\mathrm{s}} \end{aligned} \tag{31b}$$

i_{sn} is the current in the phase n expressed as

$$i_{\mathrm{sn}}(t) = I_{xn} \cdot \cos\theta_{\mathrm{s}} + I_{yn} \cdot \sin\theta_{\mathrm{s}}, \qquad n = 2, \ldots, 6 \tag{32}$$

I_{xn} and I_{yn} have to be determined and it is shown in [7] that (31) and (32) lead to a system of four equations with ten unknown variables

$$\begin{aligned} & I_{x2} \cdot \cos(\gamma) + I_{x3} \cdot \cos(2\pi/3) + I_{x4} \cdot \cos(2\pi/3+\gamma) \\ & \quad + I_{x5} \cdot \cos(4\pi/3) + I_{x6} \cdot \cos(4\pi/3+\gamma) = 3 \cdot I_{\mathrm{m}} \end{aligned} \tag{33a}$$

$$\begin{aligned} & I_{y2} \cdot \cos(\gamma) + I_{y3} \cdot \cos(2\pi/3) + I_{y4} \cdot \cos(2\pi/3+\gamma) \\ & \quad + I_{y5} \cdot \cos(4\pi/3) + I_{y6} \cdot \cos(4\pi/3+\gamma) = 0 \end{aligned} \tag{33b}$$

$$\begin{aligned} & I_{x2} \cdot \sin(\gamma) + I_{x3} \cdot \sin(2\pi/3) + I_{x4} \cdot \sin(2\pi/3+\gamma) \\ & \quad + I_{x5} \cdot \sin(4\pi/3) + I_{x6} \cdot \sin(4\pi/3+\gamma) = 0 \end{aligned} \tag{33c}$$

$$\begin{aligned} & I_{y2} \cdot \sin(\gamma) + I_{y3} \cdot \sin(2\pi/3) + I_{y4} \cdot \sin(2\pi/3+\gamma) \\ & \quad + I_{y5} \cdot \sin(4\pi/3) + I_{y6} \cdot \sin(4\pi/3+\gamma) = 3 \cdot I_{\mathrm{m}}. \end{aligned} \tag{33d}$$

To solve this system, six additional equations are required and they have to satisfy physical constraints. For example, one can impose the fact that the sum of phase currents is equal to zero if the neutral point of the machine is insulated. This gives two new equations

$$I_{x2} + I_{x3} + I_{x4} + I_{x5} + I_{x6} = 0 \tag{34a}$$

$$I_{y2} + I_{y3} + I_{y4} + I_{y5} + I_{y6} = 0. \tag{34b}$$

On the other hand, the stator copper losses are minimized if the following relations hold [5]:

$$I_{x2}^2 + I_{y2}^2 = I_{x3}^2 + I_{y3}^2 \tag{35a}$$

$$I_{x3}^2 + I_{y3}^2 = I_{x4}^2 + I_{y4}^2 \tag{35b}$$

$$I_{x4}^2 + I_{y4}^2 = I_{x5}^2 + I_{y5}^2 \tag{35c}$$

$$I_{x5}^2 + I_{y5}^2 = I_{x6}^2 + I_{y6}^2. \tag{35d}$$

Equations (33), (34), and (35) are now a set of ten nonlinear equations with ten unknown variables. In the case of a 6PIM with $\gamma = 60^\circ$, its solution is the following:

$$\begin{cases} i_{\mathrm{s2}}(t) = 1.27 I_{\mathrm{m}} \cdot \sin(\theta_{\mathrm{s}} - 60^\circ) \\ i_{\mathrm{s3}}(t) = 1.27 I_{\mathrm{m}} \cdot \sin(\theta_{\mathrm{s}} - 150^\circ) \\ i_{\mathrm{s4}}(t) = 1.27 I_{\mathrm{m}} \cdot \sin(\theta_{\mathrm{s}} - 180^\circ) \\ i_{\mathrm{s5}}(t) = 1.27 I_{\mathrm{m}} \cdot \sin(\theta_{\mathrm{s}} + 150^\circ) \\ i_{\mathrm{s6}}(t) = 1.27 I_{\mathrm{m}} \cdot \sin(\theta_{\mathrm{s}} + 60^\circ). \end{cases} \tag{36}$$

For the case of s1 open, the disturbance-free operation implies that the remaining phase currents have to be controlled by the new current configuration given by (36). It should be noted that the new current magnitude is increased in order to maintain the same torque as in the case of the healthy machine. If a reduced torque is tolerated, the current magnitude can stay at the same level I_{m} as in healthy operation. The main drawback of this method consists in solving a system of nonlinear equations which has to be done offline. Fig. 3 gives the simulation results for the estimated torque, the rotor speed and stator currents when one phase is opened.

It should be noted that the neutral point of the studied machine is insulated and the phase currents cannot be separately controlled. This is why the winding currents [Fig. 3(c)] do not exactly track their references given in (36). By comparing the response without compensation [Fig. 2(b)] and with the method 1 [Fig. 3(b)], the magnitude of the speed oscillations is reduced by about 80% when compensated.

B. Method 2

In [10], the authors propose to reduce the torque oscillations by modifying only one phase current. It has been shown that the following current applied to the phase n allows the minimization of torque oscillations:

$$i_{\mathrm{sn}}(t) = 2 \cdot I_{\mathrm{m}} \cdot \cos(\theta_{\mathrm{nj}}) \cdot \sin(\theta_{\mathrm{s}} - \varphi_j) \tag{37}$$

where θ_{nj} is the electric angle between the open phase j and the modified one n and φ_j is the open phase angle ($\varphi_j = 0$ for $j = 1$). It should be noted that the other currents are not changed. If the phase s1 is opened $(j = 1)$ and the phase s3 is chosen to be changed $(n = 3)$, the following currents are required:

$$\begin{cases} i_{\mathrm{s2}}(t) = I_{\mathrm{m}} \sin(\theta_{\mathrm{s}} - \gamma) \\ i_{\mathrm{s3}}(t) = 2 I_{\mathrm{m}} \cos(2\pi/3) \cdot \sin(\theta_{\mathrm{s}}) = -I_{\mathrm{m}} \sin(\theta_{\mathrm{s}}) \\ i_{\mathrm{s4}}(t) = I_{\mathrm{m}} \sin(\theta_{\mathrm{s}} - 2\pi/3 - \gamma) \\ i_{\mathrm{s5}}(t) = I_{\mathrm{m}} \sin(\theta_{\mathrm{s}} - 4\pi/3) \\ i_{\mathrm{s6}}(t) = I_{\mathrm{m}} \sin(\theta_{\mathrm{s}} - 4\pi/3 - \gamma). \end{cases} \tag{38}$$

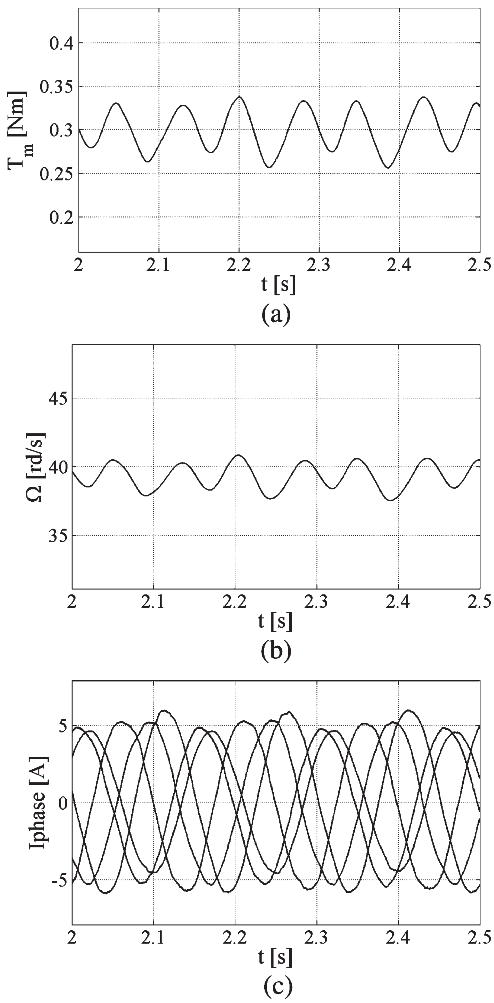

Fig. 3. Simulation results for s1 open with compensation (method 1): (a) Estimated torque, (b) rotor speed, and (c) stator currents.

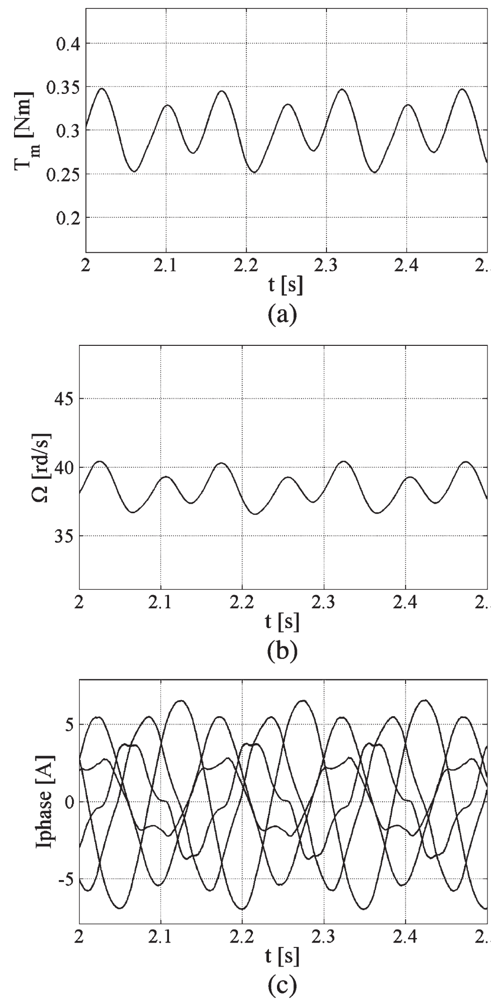

Fig. 4. Simulation results for s1 open with compensation (method 2): (a) Estimated torque, (b) rotor speed, and (c) stator currents.

This method is simple to implement and it can be easily generalized to the other cases when more than one phase is opened. However, the single current modification does not minimize the losses. Moreover, it can be shown that nonactive current components ($z1$-$z2$-$z3$) are not equal to zero when the new current set given by (38) is applied. Fig. 4 gives the new simulation results for the estimated torque, the rotor speed and the stator phase currents when one phase is opened.

By comparing the response without compensation [Fig. 2(b)] and the response obtained with the method 2 proposed in [10] [Fig. 4(b)], the magnitude of the torque oscillations is reduced by about 75% when compensated.

C. Proposed Method

According to the (30), I_α and I_β have to be proportional in order to minimize the torque oscillations. A good choice can be

$$\begin{cases} I_\alpha = k_{\mathrm{t}} \|\beta\| \cdot I_{\mathrm{m}} \\ I_\beta = k_{\mathrm{t}} \|\alpha\| \cdot I_{\mathrm{m}} \end{cases} \tag{39}$$

where k_{t} is tuned to get the expected torque.

To maintain the rated stator current magnitude, it is possible to choose $k_{\mathrm{t}} = 1$. It should be noted that the $\alpha\beta$ current choice implies that the phase current magnitudes are not the same and can take values between $k_{\mathrm{t}}\|\beta\|/\|\alpha\|$ and $k_{\mathrm{t}}\|\alpha\|/\|\beta\|$. In the case of one open phase, the current magnitudes are in the range 0.82 $k_{\mathrm{t}} I_{\mathrm{m}}$ to 1.22 $k_{\mathrm{t}} I_{\mathrm{m}}$.

Once I_α and I_β are fixed according to the (39), the $\alpha\beta$ reference currents are computed from (23) and (24). Then, according to (4), the active phase reference currents can be obtained by the transformation matrix $[T_{\mathrm{c}}]$

$$[I_{\mathrm{sref}}(\mathrm{t})] = [T_{\mathrm{c}}]^{\mathrm{T}} \begin{bmatrix} I_\alpha \sin(\theta_{\mathrm{s}}) \\ -I_\beta \cos(\theta_{\mathrm{s}}) \end{bmatrix}. \tag{40}$$

In the case of s1 open, $\|\alpha\| = \sqrt{2}$ and $\|\beta\| = \sqrt{3}$, $[T_{\mathrm{c}}]$ is written as follows:

$$[T_{\mathrm{c}}] = k_{\mathrm{t}} \begin{bmatrix} 1/\sqrt{8} & -1/\sqrt{8} & -1/\sqrt{2} & -1/\sqrt{8} & 1/\sqrt{8} \\ 1/2 & 1/2 & 0 & -1/2 & -1/2 \end{bmatrix}. \tag{41}$$

The implementation of this method is quite simple since the $\alpha\beta$ reference currents are determined by using (23), (24), and (39). Then, according to the current control strategy ($\alpha\beta$ current control or phase current control), the phase current references can also be computed from (40). These reference currents are imposed to the 6PIM stator windings using convenient current regulators. Under these conditions, the active phase currents satisfy the criterion (30) that minimizes the torque oscillations while the z-subspace currents are set to zero. Thus, the losses for a given torque are minimized. The key point of this technique is the determination of transformation matrix $[T_{\mathrm{c}}]$ according to open phase(s). To facilitate this task, a software has been developed and it can be downloaded from [20]. The inputs are the angle γ and up to three open phase numbers and the outputs are $[T_{\mathrm{c}}]$, $\|\alpha\|$ and $\|\beta\|$.

The criterion (30) can be applied in a field-oriented control scheme where the dq currents are used to control the electromagnetic torque. In this case, the $\alpha\beta$ currents have to be deduced from dq currents by a proper transformation matrix which verifies (30) to minimize the steady state torque oscillations. This transformation may be the following:

$$\begin{bmatrix} i_{\mathrm{s}\alpha\mathrm{ref}} \\ i_{\mathrm{s}\beta\mathrm{ref}} \end{bmatrix} = P(\theta_{\mathrm{s}}) \cdot \begin{bmatrix} i_{\mathrm{sdref}} \\ i_{\mathrm{sqref}} \end{bmatrix}, \qquad P(\theta_{\mathrm{s}}) = \begin{bmatrix} k_\alpha \cos\theta_{\mathrm{s}} & -k_\alpha \sin\theta_{\mathrm{s}} \\ k_\beta \sin\theta_{\mathrm{s}} & k_\beta \cos\theta_{\mathrm{s}} \end{bmatrix} \tag{42}$$

with

$$\frac{k_\alpha}{k_\beta} = \frac{M_q}{M_d} = \frac{\|\beta\|}{\|\alpha\|}. \tag{43}$$

From (43), it is obvious that there are two unknown coefficients (k_α and k_β) for only one equation. Thus, a degree of freedom is left to satisfy another criterion.

Fig. 5 depicts the simulation results for the estimated torque, the rotor speed and the stator currents when one phase is opened. By comparing the response without compensation [Fig. 2(b)] and the response with the proposed method [Fig. 5(b)], the magnitude of the speed oscillations is reduced by more than 90% when compensated.

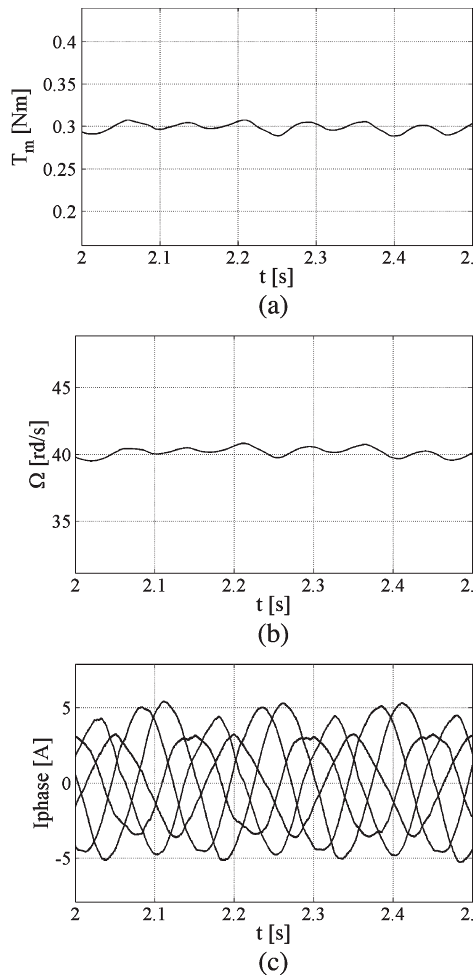

Fig. 5. Simulation results for s1 open with the proposed compensation method: (a) Estimated torque, (b) rotor speed, and (c) stator currents.

V. Experimental Results

To verify the efficiency of the proposed method, an experimental test-rig bed has been developed (Fig. 6). It is composed of a 6PIM supplied by two three-phase VSIs whose dc link voltage is 42 V. The switching frequency is set at 5 kHz using the classical sampled natural PWM technique generated by an FPGA. The digital control board has been built around an Intel-Pentium 4 processor allowing easily an actual sampling period of 200 μs. This board receives the stator current data through six 12-bit A/D converters. An electromagnetic powder brake stiffly connected to the 6PIM rotor shaft is used to generate the load torque. The speed is measured through a 4096-points encoder. The 6PIM drive main parameters are given in Table II.

To open phase s1, the corresponding VSI winding connection is removed. Four tests have been performed at a low stator electrical frequency (42 rad/s) in order to show the efficiency of the proposed technique compared to the others. In the first test, there is no compensation (Fig. 7), while in the others (Figs. 8–10) the stator phase current references are, respectively, fixed according to one of the compensation methods presented before.

Fig. 7 illustrates the estimated torque, the measured rotor speed and the stator currents when phase s1 is opened at about $t = 0.8$ s without any compensation.

It should be noted that there is no torque sensor and therefore the torque is estimated using the 6PIM model and the measured currents. In order to verify the efficiency of the above methods, the speed oscillations with and without compensation are compared.

Fig. 7(a) and (d) represent the simulated and experimental estimated torque for s1 open at $t = 0.8$ s without any compensation, while Fig. 7(b) and (e) represent the simulated and experimental speed and Fig. 7(c) and (d) depict the simulated and experimental stator phase currents. As can be seen, low frequency oscillations appear in the rotor speed underlining torque ripples. The frequency of these oscillations is twice that of the stator currents ($\omega_{\mathrm{s}} = 42$ rad/s) as expected. In all experimental tests given herewith, the frequency of the stator currents are imposed by the control and the 6PIM is acting at rated load (rated slip of 0.027). PI current controllers are used to control the magnitudes of all phase currents.

Fig. 8 illustrates the experimental results at steady state for the estimated torque, the rotor speed and the stator currents when phase s1 is opened with the compensation method 1.

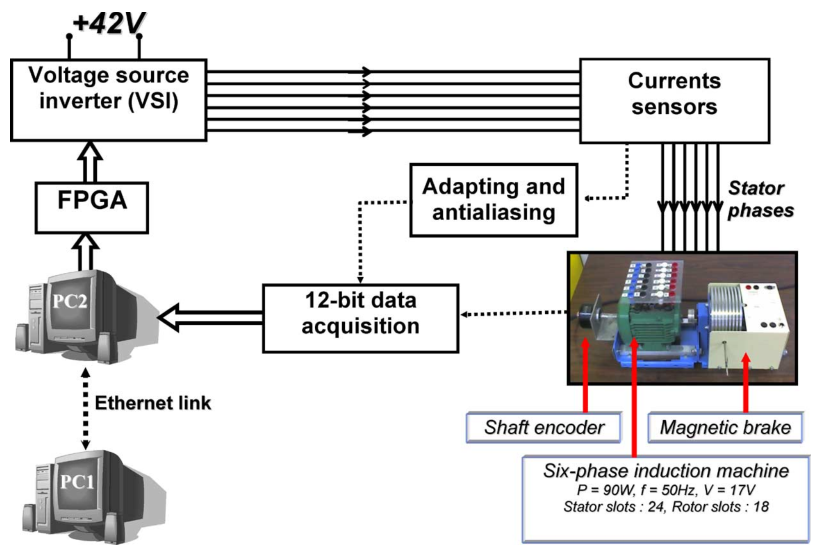

Fig. 6. Experimental test-rig.

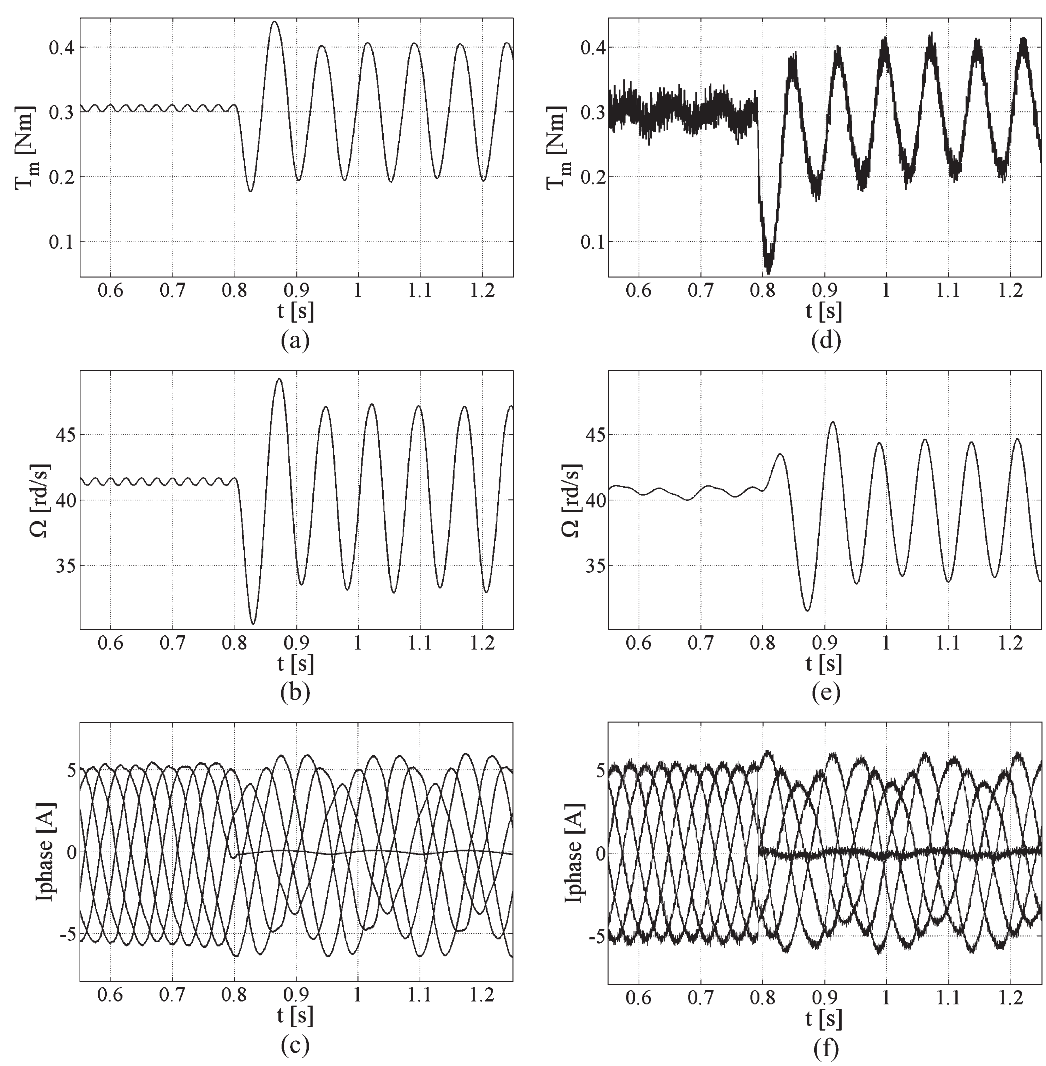

Fig. 7. (Left) Simulation and (right) experimental results for s1 open at $t = 0.8$ s without any compensation: (a) and (d) Estimated torque, (b) and (e) rotor speed, (c) and (f) stator currents.

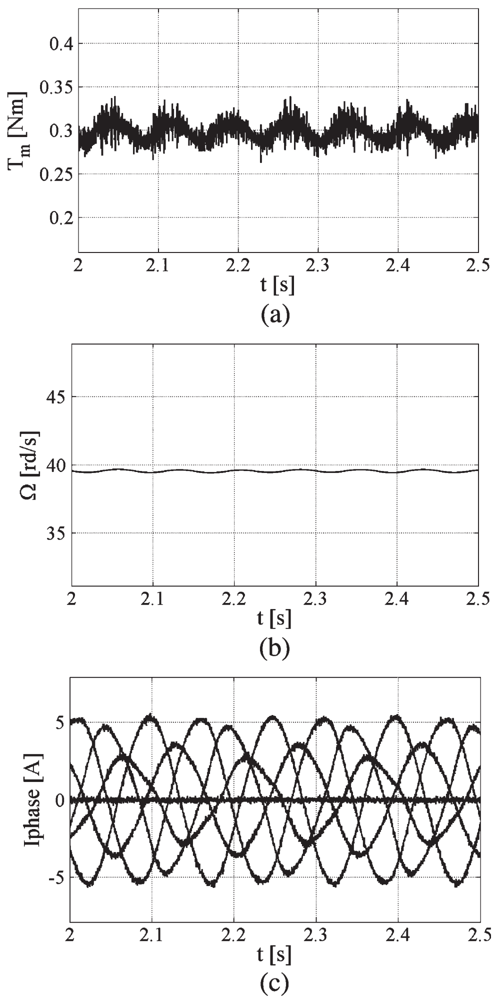

Fig. 8. Experimental results for s1 open with compensation (method 1): (a) estimated torque, (b) rotor speed, and (c) stator currents.

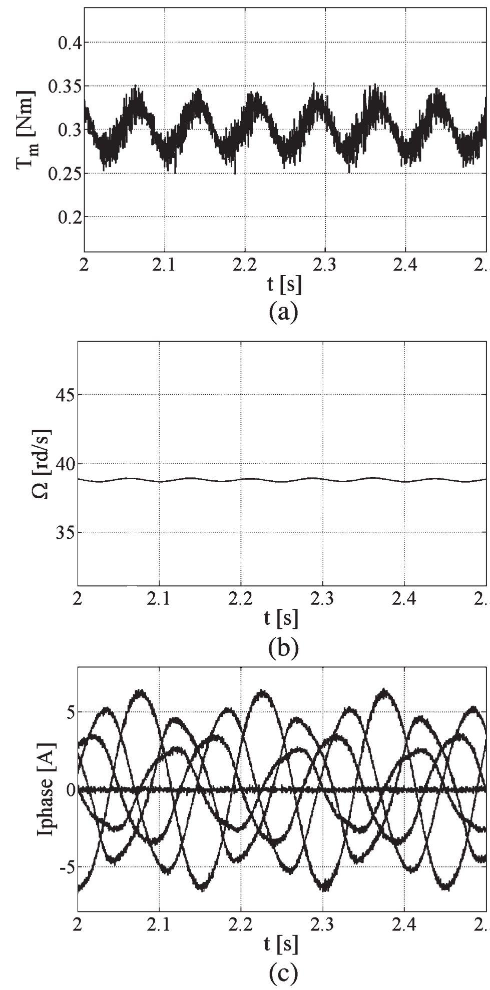

Fig. 9. Experimental results for s1 open with compensation (method 2): (a) Estimated torque, (b) rotor speed, and (c) stator currents.

These results have to be compared with those obtained by simulation (Fig. 3) and they are very similar. The reduction of torque oscillations achieved with the compensation method 1 is significant which confirms what has been observed in the simulation results. The six-phase current magnitudes are similar to what has been obtained by simulation as well due to the high switching frequency of the VSI and the high leakage inductance of the 6PIM. However, the distortion of the lowest magnitude phase current is more important than what has been predicted in simulation. This is due to the fact that the MMF is not really sinusoidal as it has been assumed in the 6PIM model.

Fig. 9 illustrates the experimental results at steady state for the estimated torque, the rotor speed and stator currents when phase s1 is opened with the compensation method 2. As in the former case, these results have to be compared with those obtained by simulation (Fig. 4) and they are similar as well. The reduction of the torque oscillations achieved with the compensation method 2 is significant as observed in the simulation results. The six-phase current magnitudes are also similar to what has been simulated even with the VSI switching frequency effects. In this case, the distortion of the two lowest magnitude phase currents is less than what has been observed in simulation because of the frequency bandwidth of the current controllers.

Fig. 10 is dedicated to the experimental results at steady state for the estimated torque, the rotor speed and the stator phase currents when phase s1 is opened with the proposed compensation method. As in the former cases, these results can be compared with those obtained by simulation (Fig. 5) and they are very similar as in the previous cases. The torque oscillations are reduced efficiently by the proposed method as it can be verified by the measured rotor speed which has less oscillation compared to what has been observed in Fig. 7 for the test without compensation. The six-phase current magnitudes are also similar to what has been simulated. As for the compensation method 2, the distortion of the two lower phase currents is less than what has been observed in the simulation results and this confirms the efficiency of the proposed method. It should be noted that for the first two methods, the stator phase currents are directly controlled in the phase reference frame while for the proposed method the stator current control is performed in the $\alpha\beta$ reference frame.

An important point is the experimental evaluation of the losses with the three compensation methods (Fig. 11). The input power is the sum of the six products of phase voltages and currents and the output power is the product of the rotor speed by the estimated torque. The machine losses can be computed

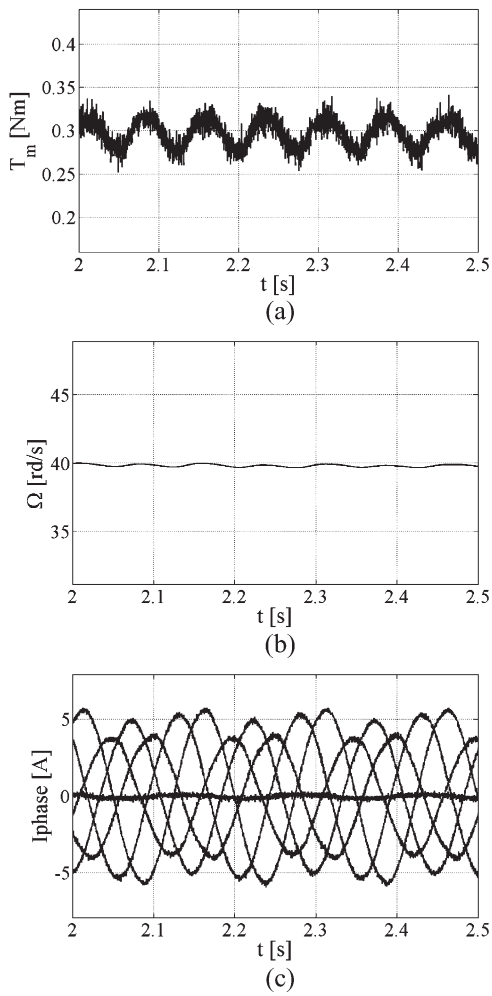

Fig. 10. Experimental results for s1 open with proposed compensation method: (a) Estimated torque, (b) rotor speed, and (c) stator currents.

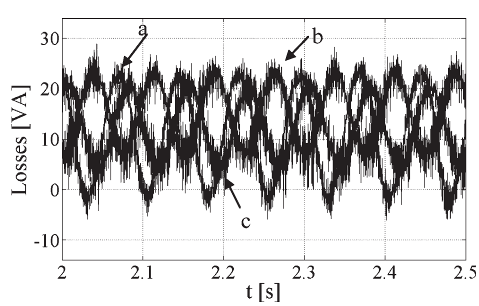

Fig. 11. Experimental results for s1 open: Estimated losses with the three compensation techniques: (a) Method 1, (b) method 2, and (c) proposed method.

as the mean value of the difference between the input power and the output power.

As expected, the average losses are lower with the proposed technique than in the two other methods. Indeed, the mean values of the losses are 12.4, 15, and 11 W for method 1, method 2, and the proposed compensation method, respectively.

VI. Conclusion

A new general model for static and dynamic analysis of a symmetrical 6PIM has been proposed. This model is very general and it can be used for up to three open stator phases by applying a convenient rotating reference frame with $\alpha\beta z$ components. The model allowed to compute the instantaneous electromagnetic torque and to evaluate its oscillations during steady state. It has been shown that the loss of at least one stator phase produces electromagnetic torque oscillations at twice the frequency of the stator current with a magnitude depending on the difference between the $\alpha\beta$-subspace current components. A proper choice of these components ratio minimizes the torque oscillation magnitude. It is shown that the proposed method can even reduce the motor losses compared to the classical compensation techniques already presented in the literature. The efficiency of the proposed technique has been shown using a dedicated test-rig with a symmetrical 6PIM and a six-phase VSI connected on a 42-V dc bus.

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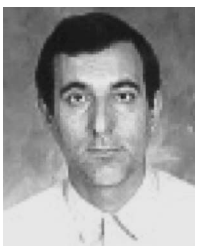

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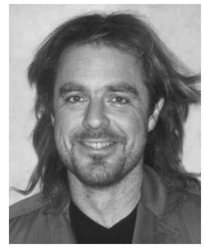

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