Multi-phase Synchronous Motors: Minimum Dissipation Fault-Tolerant Controls

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***Abstract*—Multi-phase electrical motors offer high reliability thanks to their capability to operate safely even in case of faults such the loss of one or more phases. This paper deals with the control of multi-phase permanent magnet synchronous motors under open-phase fault condition. Using a vectorial approach the optimal current references in fault condition which provide the desired torque minimizing the dissipation are obtained and used in the control law. The approach is as general as possible: the proposed control law can be used for any shape of the rotor flux, for a generic odd number of phases and in presence of one or more phase failures.**

I. INTRODUCTION

In safety critical applications, i.e. propulsion and traction applications, the reliability is a very important issue. Using classical three-phase motor drives the reliability to one fault is reached increasing the redundancy of the actuator system, using two motors and two inverters, or modifying the power converter topology, see [1].

The most important advantage of multi-phase machines compared to three-phase one is the fault-tolerant capability of the motor drive: it can continue to operate with one or more failures (the theoretical maximum number of faults is $m_s - 3$). In [2] and [3] a multi-phase synchronous motor is designed with a modular approach minimizing the electrical, magnetic and thermal coupling between the windings. Thus, a failure in one winding will not affect the operation of the remaining windings. However if the control is not modified the mean value of the torque reduces and a torque ripple appears. Therefore a reconfiguration of the control strategy for the remaining healthy phases is necessary to compensate the fault effect. In this way the performance of the system would appear unaffected.

In this paper the minimum dissipation control of a multi-phase PM machine in the case of open circuited phases is studied. Using the proposed control strategy the multi-phase motor continues to operate safely (generating the same desired torque without ripple) under a phase-fault without any additional hardware connections. The approach is quite general: the proposed control law can be used for any shape of the rotor flux, for a generic odd number of phases and it works in presence of one or more failures.

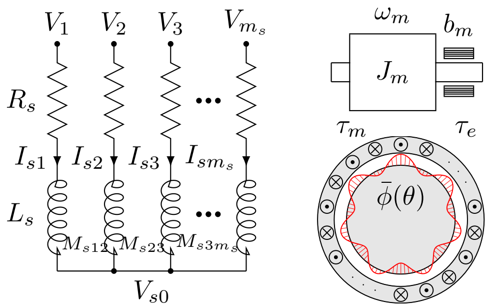

Fig. 1. Basic structure of a multi-phase synchronous motor.

The paper is organized as follows. Sec. II shows the details of the dynamic model of the m_s-phase synchronous motors, in Sec. III the control of the motor in open phase fault condition is presented and Sec. IV is devoted to simulation results. Conclusions are given in Sec. V.

A. Notations

The symbols $\left\|\left[\, R_i \,\right]\right\|_{1:n}^{i}$ and $\left|\left[\, R_i \,\right]\right|_{1:n}^{i}$ will denote the column and row matrices, while the full matrix will be denoted as:

$$\left\|\left[\, R_{i,j} \,\right]\right\|_{1:n \;\; 1:m}^{i \;\;\;\; j} = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1m} \\ R_{21} & R_{22} & \cdots & R_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n1} & R_{n2} & \cdots & R_{nm} \end{bmatrix}.$$

The symbol $\sum_{n=a:d}^{b} c_n = c_a + c_{a+d} + c_{a+2d} + \ldots$ will be used to represent the sum of a succession of numbers c_n where the index n ranges from a to b with increment d. The symbols $\mathbf{1}^m$ and $\mathbf{0}^m$ will represent ones and zeros column vectors of dimensions m. Symbols Im$(\mathbf{A})$ and Ker$(\mathbf{A})$ will denote the image and the kernel subspaces of matrix $\mathbf{A}$.

II. ELECTRICAL MOTORS MODELING

The basic structure of a multi-phase synchronous motor is shown in Fig. 1. In this paper we refer to a permanent magnet synchronous motor with an *odd* number m_s of star connected concentrated windings [4]-[5] characterized by the parameters shown in Tab. I. The assumptions of regularity of the design and no

m_s	number of motor phases
p	number of polar expansions
θ, θ_m	electric and rotor angular positions: $\theta = p\,\theta_m$
ω, ω_m	electric and rotor angular velocities: $\omega = p\,\omega_m$
R_s	i-th stator phase resistance
L_s	i-th stator phase self induction coefficient
M_{s0}	maximum value of the stator mutual inductance
J_m	rotor moment of inertia
b_m	rotor linear friction coefficient
τ_m	electromotive torque acting on the rotor
τ_e	external load torque acting on the rotor
γ_s	basic angular displacement ($\gamma_s = 2\pi/m_s$)
$\phi_c(\theta)$	total rotor flux chained with stator phase 1
φ_c	maximum value of function $\phi_c(\theta)$
$\bar{\phi}(\theta)$	normalized total rotor flux: $\bar{\phi}(\theta) = \frac{\phi_c(\theta)}{\varphi_c} = \sum_{n=1:2}^{\infty} a_i \cos(n\,\theta)$

TABLE I
MAIN PARAMETERS OF A MULTI-PHASE SYNCHRONOUS MOTOR.

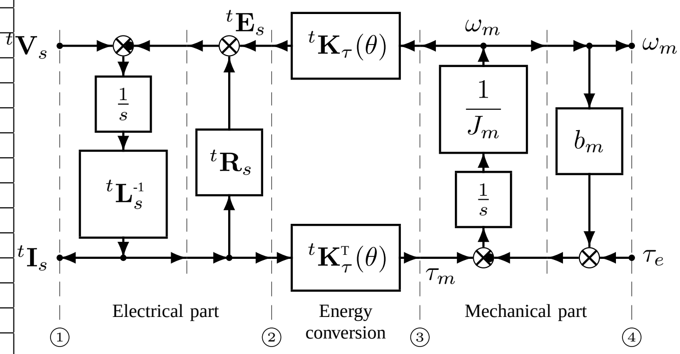

Fig. 2. POG block scheme of the dynamic model of a multi-phase synchronous motor in the fixed reference frame Σ_t.

iron saturation will be considered in this analysis. Let us introduce the following current and voltage stator vectors: $^t\mathbf{I}_s = \left[I_{s1} \cdots I_{sm_s}\right]^{\mathrm{T}}$, $^t\mathbf{V}_s = \left[V_{s1} \cdots V_{sm_s}\right]^{\mathrm{T}}$ where V_{si} is the i-th phase voltage referred to the common voltage V_{s0}: $V_{si} = V_i - V_{s0}$.
Using a "Lagrangian" approach, see [5], the dynamic model S_t of the considered electric motor with respect to the external fixed frame Σ_t is the following:

$$\left[\begin{array}{c|c} ^t\mathbf{L}_s & \mathbf{0} \\ \hline \mathbf{0} & J_m \end{array}\right]\left[\begin{array}{c} ^t\dot{\mathbf{I}}_s \\ \hline \dot{\omega}_m \end{array}\right] = -\left[\begin{array}{c|c} ^t\mathbf{R}_s & ^t\mathbf{K}_\tau(\theta) \\ \hline -^t\mathbf{K}_\tau^{\mathrm{T}}(\theta) & b_m \end{array}\right]\left[\begin{array}{c} ^t\mathbf{I}_s \\ \hline \omega_m \end{array}\right] + \left[\begin{array}{c} ^t\mathbf{V}_s \\ \hline -\tau_e \end{array}\right] \tag{1}$$

where $^t\mathbf{R}_s = R_s\,\mathbf{I}_{m_s}$ and the inductance matrix $^t\mathbf{L}_s$ is:

$$^t\mathbf{L}_s = L_{s0}\,\mathbf{I}_{m_s} + {}^t\mathbf{M}_s = L_{s0}\,\mathbf{I}_{m_s} + M_{s0} \mathop{[\![}_{1:m_s}^{i} \cos((i-h)\gamma_s) \mathop{]\!]}_{1:m_s}^{h}$$

with $L_{s0} = L_s - M_{s0}$. According to the magnetic co-energy method the torque τ_m and the back-electromotive force $^t\mathbf{E}_s$ are:

$$\tau_m = {}^t\mathbf{K}_\tau^{\mathrm{T}}\,{}^t\mathbf{I}_s\,, \qquad {}^t\mathbf{E}_s = {}^t\mathbf{K}_\tau \omega_m = \mathop{[\![}_{1:m_s}^{h} E_{sh}]\!]$$

where the torque vector $^t\mathbf{K}_\tau(\theta)$ is function of the electric angle θ and the coefficients a_n of the flux Fourier series shown in Tab. I as follows:

$$^t\mathbf{K}_\tau(\theta) = \frac{\partial\, {}^t\mathbf{\Phi}_c(p\,\theta_m)}{\partial \theta_m} = p\,\varphi_c \mathop{\left[\!\!\left[-\sum_{n=1:2}^{\infty} n a_n \sin\left(n(\theta - h\gamma_s)\right) \right]\!\!\right]}_{1:m_s}^{h}. \tag{2}$$

Using the Power-Oriented Graphs modeling technique, see [6], one obtains the POG block scheme of the synchronous motor in the fixed reference frame Σ_t shown in Fig. 2. The *elaboration blocks* between power sections ① and ② represent the *Electrical part* of the system, while the blocks between sections ③ and ④ represent the *Mechanical part* of the system. The *connection block* between sections ② and ③ represents the energy and power conversion between the electrical and mechanical parts of the motor.

III. MINIMUM DISSIPATION TORQUE CONTROL IN FAULT CONDITION

A. Control in the fixed reference frame

The current vector $^t\mathbf{I}_d$ which provides the desired torque τ_d minimizing the power dissipation is the vector with the minimum modulus parallel to the torque vector $^t\mathbf{K}_\tau(\theta)$:

$$^t\mathbf{I}_d(\theta) = \frac{\tau_d}{|\,^t\mathbf{K}_\tau(\theta)|}\,{}^t\hat{\mathbf{K}}_\tau(\theta) = \frac{^t\mathbf{K}_\tau(\theta)}{|\,^t\mathbf{K}_\tau(\theta)|^2}\,\tau_d. \tag{3}$$

where $^t\hat{\mathbf{K}}_\tau(\theta)$ denotes the versor of vector $^\omega\mathbf{K}_\tau$ defined in (2). When f phase-faults occur the related phase currents fall down to zero and they do not contribute any more to the torque generation. In this case the open phase constraints can be taken into account projecting the torque vector onto the $m_s - f$ dimensional subspace generated by the healthy currents. Let $\mathcal{S} = \{i_1, i_2, ..., i_f\}$ denote the index set of the faulty phases with $f \le m_s - 3$. In the case of a star connected motor the open phase constraints can be written as:

$$\underline{^t\mathbf{B}}^{\mathrm{T}}\,{}^t\mathbf{I}_s = \left[\sum_{i=1}^{m_s} I_{si}\,,\, I_{si_1}\,,\, I_{si_2}\,, \cdots, I_{si_f}\right]^{\mathrm{T}} = (\mathbf{0}^{f+1})^{\mathrm{T}}$$

where matrix $\underline{^t\mathbf{B}}$ is defined as follows:

$$\underline{^t\mathbf{B}} = \left[\mathbf{1}^{m_s}\ \ {}^t\mathbf{B}\right], \qquad {}^t\mathbf{B} = [\ \mathbf{e}_{i_1}^{m_s}\ \mathbf{e}_{i_2}^{m_s}\ \cdots\ \mathbf{e}_{i_f}^{m_s}]. \tag{4}$$

Note that in matrix $\underline{^t\mathbf{B}}$ the vector $\mathbf{1}^{m_s}$ is used to taken into account the star connection constraint, while matrix $^t\mathbf{B}$ selects the faulty component (the i-th standard basis vector $\mathbf{e}_i^{m_s}$ of space $\mathbb{R}^{m_s}$ is used to select the i-th fault component I_{si} of the current vector $^t\mathbf{I}_s$). The vectors $\mathbf{1}^{m_s}, \mathbf{e}_{i_1}^{m_s}, \mathbf{e}_{i_2}^{m_s}, \cdots$ and $\mathbf{e}_{i_f}^{m_s}$ form a basis of the f-dimensional forbidden subspace Im($\underline{^t\mathbf{B}}$). The subspace Ker($\underline{^t\mathbf{B}}^{\mathrm{T}}$), which is orthogonal to the forbidden subspace Im($\underline{^t\mathbf{B}}$), it the subspace of the healthy currents

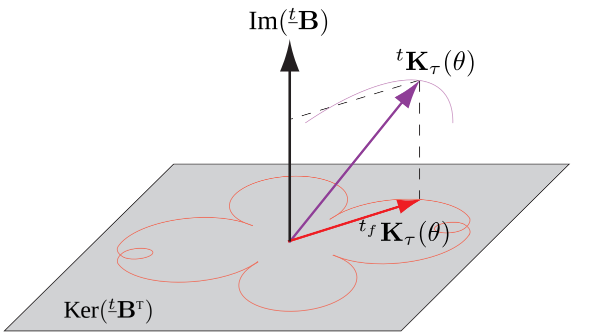

Fig. 3. Projection of a torque vector onto the subspace of healthy currents.

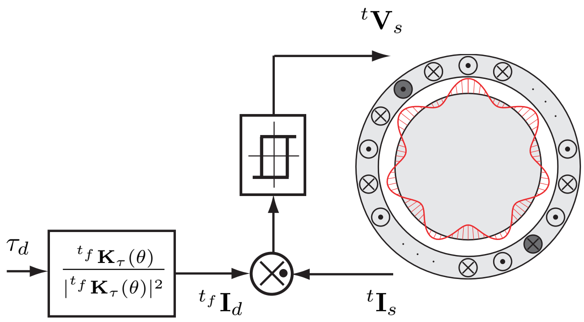

Fig. 4. Multi-phase control motor drive under fault condition in fixed reference frame.

that satisfy the constraints. Therefore the current constraints are satisfied if the torque vector ${}^{t}\mathbf{K}_\tau(\theta)$ is projected on Ker(${}^{\underline{t}}\mathbf{B}^{\mathrm{T}}$) along Im(${}^{\underline{t}}\mathbf{B}$). The projection matrix $\mathbf{P}$ on Ker(${}^{\underline{t}}\mathbf{B}^{\mathrm{T}}$) along Im(${}^{\underline{t}}\mathbf{B}$) is defined as follows:

$$\mathbf{P} = \mathbf{I}_{m_s} - {}^{\underline{t}}\mathbf{B}\left({}^{\underline{t}}\mathbf{B}^{\mathrm{T}}\,{}^{\underline{t}}\mathbf{B}\right)^{-1}{}^{\underline{t}}\mathbf{B}^{\mathrm{T}}.$$

The projected torque vector ${}^{tf}\mathbf{K}_\tau(\theta)$ is obtained as follows:

$${}^{tf}\mathbf{K}_\tau(\theta) = \mathbf{P}\,{}^{t}\mathbf{K}_\tau(\theta) = \left[\mathbf{I}_{m_s} - {}^{\underline{t}}\mathbf{B}\left({}^{\underline{t}}\mathbf{B}^{\mathrm{T}}\,{}^{\underline{t}}\mathbf{B}\right)^{-1}{}^{\underline{t}}\mathbf{B}^{\mathrm{T}}\right]{}^{t}\mathbf{K}_\tau(\theta) \tag{5}$$

A graphical representation of equation (5) is shown in Fig. 3 where the torque vector ${}^{t}\mathbf{K}_\tau(\theta)$, the forbidden subspace Im(${}^{\underline{t}}\mathbf{B}$) and the projected torque vector ${}^{tf}\mathbf{K}_\tau(\theta)$ are respectively described by the violet, black and red vectors. Note that the projected torque vector ${}^{tf}\mathbf{K}_\tau(\theta)$ describes a complex symmetrical trajectory on the subspace Ker(${}^{\underline{t}}\mathbf{B}^{\mathrm{T}}$) of the healthy currents because it is a nonsymmetrical vector with zeros in correspondence of the components related to the faulty phases. Moreover if the rotor flux function is characterized by the first odd $m_s - 2$ harmonics, the modulus of torque vector $|{}^{t}\mathbf{K}_\tau(\theta)|$ is constant while the modulus of the projected torque vector $|{}^{tf}\mathbf{K}_\tau(\theta)|$ is a periodic function of the electric angle. Substituting equation (5) in (3) one obtains in fault condition the current vector ${}^{tf}\mathbf{I}_d(\theta)$ which provides the desired torque τ_d satisfying the constraints and minimizing the power dissipation:

$${}^{tf}\mathbf{I}_d(\theta) = \frac{{}^{tf}\mathbf{K}_\tau(\theta)}{|{}^{tf}\mathbf{K}_\tau(\theta)|^2}\,\tau_d. \tag{6}$$

Note that in the fixed reference frame Σ_t the current and voltage vectors ${}^{t}\mathbf{I}_s(\theta)$ and ${}^{t}\mathbf{V}_s(\theta)$ are functions of the electrical position θ. Moreover the magnetic coupling between the phases (described by the full inductance matrix ${}^{t}\mathbf{L}_s$) makes difficult the achievement of the control scheme. In these conditions an hysteresis current controller can be used in order to follow the time variant reference current vector ${}^{tf}\mathbf{I}_d(\theta)$, see Fig. 4.
Equation (6) has been found with different approach in [7] and [8]. In [7] the current vector in faulty conditions is obtained using the Lagrangian multipliers with the minimum dissipation function subject to the open phase and the star connection constraints. In [8] a vectorial approach is used to directly project the torque vector (named *speed normalized back electromotive force*) on the subspace of the healthy currents and imposing the star connection constraint.
The main difference of the approach proposed in this paper respect to the others in [7] and [8] is that our approach can be extended also in the rotating reference frame (also know as *dq-reference frame*) where a constant torque can be reached using a feed-forward action and a PI controller.

B. Control in the rotating reference frame

The dynamic model (1) of the multi-phase synchronous motor can be expressed in the rotating frame Σ_ω using a state space transformation ${}^{t}\mathbf{I}_s = {}^{t}\mathbf{T}_\omega\,{}^{\omega}\mathbf{I}_s$ based on the following orthonormal matrix ${}^{t}\mathbf{T}_\omega \in \mathbb{R}^{m_s\times m_s-1}$, see [9]:

$${}^{t}\mathbf{T}_\omega = \sqrt{\frac{2}{m_s}}\left\|\left\|\left[\cos(k(h\gamma_s-\theta))\;,\;\sin(k(h\gamma_s-\theta))\right]\right\|^{h}_{0:m_s-1}\right\|^{k}_{1:2:m_s-2}. \tag{7}$$

The transformed current vector ${}^{\omega}\mathbf{I}_d$ which provides the desired torque τ_d minimizing the power dissipation is the vector with the minimum modulus parallel to the transformed torque vector ${}^{\omega}\mathbf{K}_\tau$:

$${}^{\omega}\mathbf{I}_d = \frac{\tau_d}{|{}^{\omega}\mathbf{K}_\tau|}\,{}^{\omega}\hat{\mathbf{K}}_\tau = \frac{{}^{\omega}\mathbf{K}_\tau}{|{}^{\omega}\mathbf{K}_\tau|^2}\,\tau_d. \tag{8}$$

where ${}^{\omega}\hat{\mathbf{K}}_\tau$ denotes the versor of the transformed torque vector ${}^{\omega}\mathbf{K}_\tau$. If the harmonics a_k of the rotor flux function $\bar{\phi}(\theta)$ with $k > m_s$ are neglected, the transformed torque vector ${}^{\omega}\mathbf{K}_\tau$ is constant (i.e. it is not function of the electric angle θ) with the following structure:

$${}^{\omega}\mathbf{K}_\tau = {}^{t}\mathbf{T}_\omega^{\mathrm{T}}\,{}^{t}\mathbf{K}_\tau(\theta) = \varphi_c\,p\sqrt{\frac{m_s}{2}}\left\|\begin{bmatrix}0\\ k\,a_k\end{bmatrix}\right\|^{k}_{1:2:m_s-2}. \tag{9}$$

Since the transformed current vector is ${}^{\omega}\mathbf{I}_s = {}^{t}\mathbf{T}_{\omega}^{\mathrm{T}}\,{}^{t}\mathbf{I}_s$, then the open phase constraint can be written as:

$$ {}^{t}\mathbf{B}^{\mathrm{T}}\,{}^{t}\mathbf{I}_s = {}^{t}\mathbf{B}^{\mathrm{T}}\,{}^{t}\mathbf{T}_{\omega}\,{}^{\omega}\mathbf{I}_s = (\mathbf{0}^{f})^{\mathrm{T}} \tag{10} $$

where matrix ${}^{t}\mathbf{B}$ is defined in (4). The constraint matrix ${}^{\omega}\mathbf{B}$ in the rotating reference frame can be written as follows:

$$ {}^{\omega}\mathbf{B} = ({}^{t}\mathbf{B}^{\mathrm{T}}\,{}^{t}\mathbf{T}_{\omega})^{\mathrm{T}} = {}^{t}\mathbf{T}_{\omega}^{\mathrm{T}}\,{}^{t}\mathbf{B} = {}^{\omega}\mathbf{T}_{t}\,{}^{t}\mathbf{B}. $$

One first difference with the previous approach is that matrix ${}^{\omega}\mathbf{B}$ imposes only the fault constraints because it is the transformation matrix ${}^{t}\mathbf{T}_{\omega}$ that imposes the star connection constraint. On the contrary, in the fixed frame Σ_t matrix ${}^{t}\mathbf{B}$ imposes both the constraints. Now the projection matrix is:

$$ {}^{\omega}\mathbf{P} = \mathbf{I}_{m_s-1} - {}^{\omega}\mathbf{B}\left({}^{\omega}\mathbf{B}^{\mathrm{T}}\,{}^{\omega}\mathbf{B}\right)^{-1}{}^{\omega}\mathbf{B}^{\mathrm{T}}. $$

The projected torque vector ${}^{\omega_f}\mathbf{K}_{\tau}(\theta)$ is the following:

$$ {}^{\omega_f}\mathbf{K}_{\tau}(\theta) = {}^{\omega}\mathbf{P}\,{}^{\omega}\mathbf{K}_{\tau}(\theta). \tag{11} $$

A graphical representation of equation (11) at two different time t' and t, with $t' < t$, is shown in Fig. 5: the transformed torque vector ${}^{\omega}\mathbf{K}_{\tau}(\theta)$ (the violet vector) is constant while the forbidden subspace $\mathrm{Im}({}^{\omega}\mathbf{B})$ (the black vector) is function of the electric angle θ. Note that the variation of the forbidden subspace from $\mathrm{Im}({}^{\omega}\mathbf{B}')$ to $\mathrm{Im}({}^{\omega}\mathbf{B})$ modifies from $\mathrm{Ker}({}^{\omega}\mathbf{B}'^{\mathrm{T}})$ to $\mathrm{Ker}({}^{\omega}\mathbf{B}^{\mathrm{T}})$ the subspace of the healthy currents satisfying the fault constraints. In Fig. 5, the projection of the transformed torque vector ${}^{\omega_f}\mathbf{K}_{\tau}(\theta)$ (the red vector) is a periodic function of the electric angle and it describes a periodic trajectory (the red line). Note that the trajectory is the same of Fig. 3 because it is possible to prove that the following relation holds:

$$ |\,{}^{t_f}\mathbf{K}_{\tau}(\theta)| = |\,{}^{\omega_f}\mathbf{K}_{\tau}(\theta)|. $$

Substituting equation (11) in (8) one obtains the desired current vector ${}^{\omega_f}\mathbf{I}_d$ in frame Σ_{ω} under fault condition which provides the desired torque τ_d minimizing the power dissipation:

$$ {}^{\omega_f}\mathbf{I}_d = \frac{\tau_d}{|{}^{\omega_f}\mathbf{K}_{\tau}|}\,{}^{\omega_f}\hat{\mathbf{K}}_{\tau} = \frac{{}^{\omega_f}\mathbf{K}_{\tau}}{|{}^{\omega_f}\mathbf{K}_{\tau}|^2}\,\tau_d. \tag{12} $$

The constant torque τ_d can be achieved using the following control:

$$ {}^{\omega}\mathbf{V}_s = ({}^{\omega}\mathbf{R}_s + {}^{\omega}\mathbf{J}_s\,{}^{\omega}\mathbf{L}_s)\,{}^{\omega}\mathbf{I}_s + {}^{\omega}\mathbf{K}_{\tau}\,\omega_m - \mathbf{K}_c({}^{\omega}\mathbf{I}_s - {}^{\omega_f}\mathbf{I}_d) \tag{13} $$

where $\mathbf{K}_c$ is a diagonal matrix, used for the control design, defined as follows:

$$ \mathbf{K}_c = K\frac{2\omega^2}{s^2 + (2\omega)^2}(s+2\omega)^2\mathbf{I}_{m_s-1}. \tag{14} $$

Matrix $\mathbf{K}_c$ has been obtained using the Internal Model Principle because the direct and quadrature components of the current vector in (8) oscillate at frequencies 2ω, 4ω, ... $(m_s-2+l)\omega$. Note that the first part of equation (14) allows to track reference current vectors while the second order term $(s+2\omega)^2$ stabilizes the system. The equations (8) and (13) are used together in the control block diagram shown in Fig. 6.

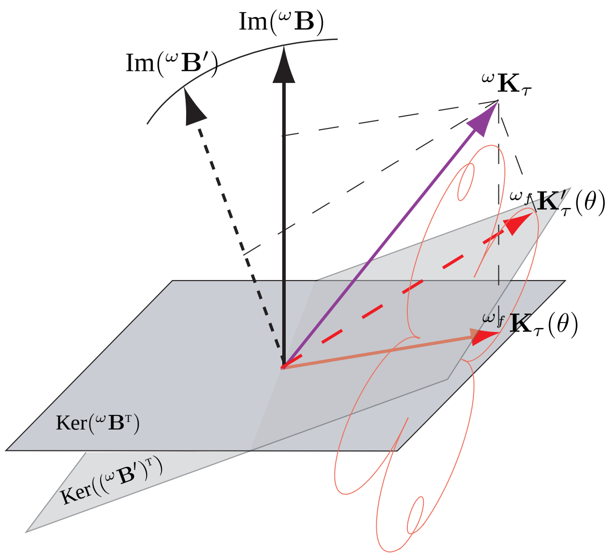

Fig. 5. Projection of a torque vector onto the subspace of healthy currents.

IV. SIMULATIONS

Both the control diagrams in Fig. 4 and Fig. 6 have been implemented in Matlab-Simulink. The POG model of the electrical motor in faulty condition is described in [10]. This model simulates the failure with an additional voltage such that the steady-state currents of the open phases are zero.

The simulation results shown in this section have been obtained using the following electrical and mechanical parameters: $m_s = 7$, $p = 1$, $R_s = 2\,\Omega$, $L_s = 0.03$ H, $M_{s0} = 0.02$ H, $\varphi_r = 0.02$ Wb, $J_m = 1.6$ kg m^2, $b_m = 0.8$ Nm s/rad, $a_1 = 1$, $a_3 = 0.28$, $a_5 = 0.125$, desired torque $\tau_d = 30$ Nm and external torque $\tau_e = 0$ Nm.

The stator currents ${}^{t}\mathbf{I}_s$ in the fixed reference frame obtained using control (6) and control (8) are shown in Fig. 7 and in Fig. 8, respectively. Note that at time $t_1 = 1.5$ s phase 6 opens and current I_{s6} goes to zero. Then at time $t_3 = 4$ s phase 3 opens and current I_{s3} goes to zero with $I_{s6} = 0$. The fault tolerant control is activated at time $t_2 = 1.5$ s and at time $t_4 = 4.5$ s. The motor velocity ω_m and the motor torque τ_m are shown in Fig. 9. When the first open-phase fault occurs the mean value of the torque reduces and the torque ripple appears because between t_1 and t_2 the control is unchanged respect the healthy condition. At time t_2 when the fault tolerant control is applied the torque grows to the desired value $\tau_d = 30$ Nm without ripple. When the second open-phase fault occurs the mean value of the torque reduces again and the torque ripple appears because between t_3 and t_4 there are two

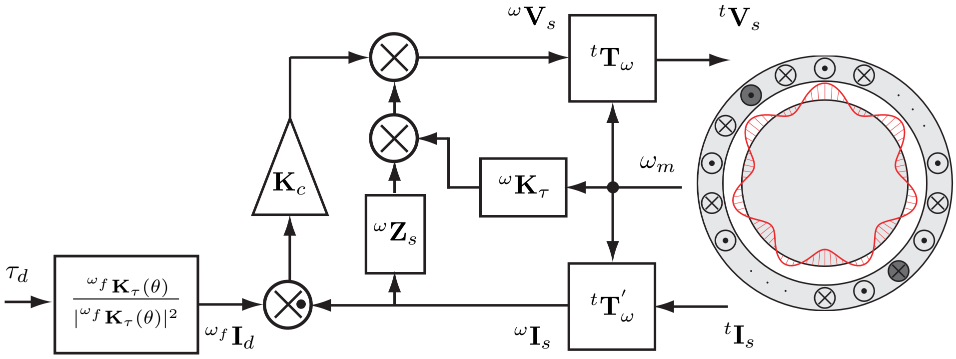

Fig. 6. Multi-phase control motor drive scheme under fault condition in rotating reference frame.

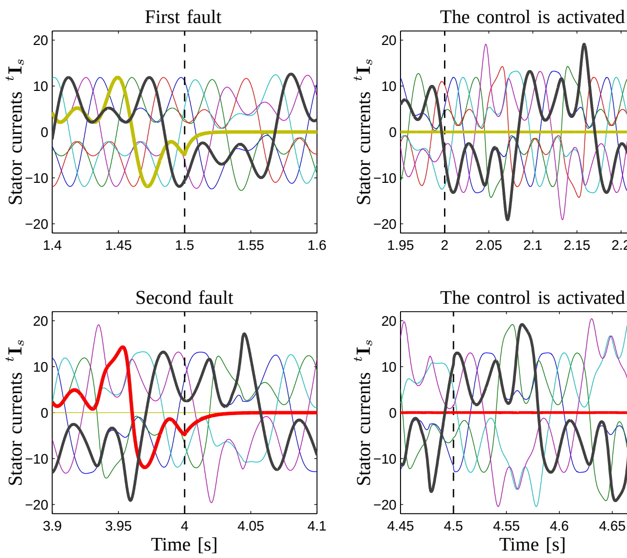

Fig. 7. Stator currents $^{t}\mathbf{I}_s$ in the fixed reference frame obtained using the control law described in Sec. III-A .

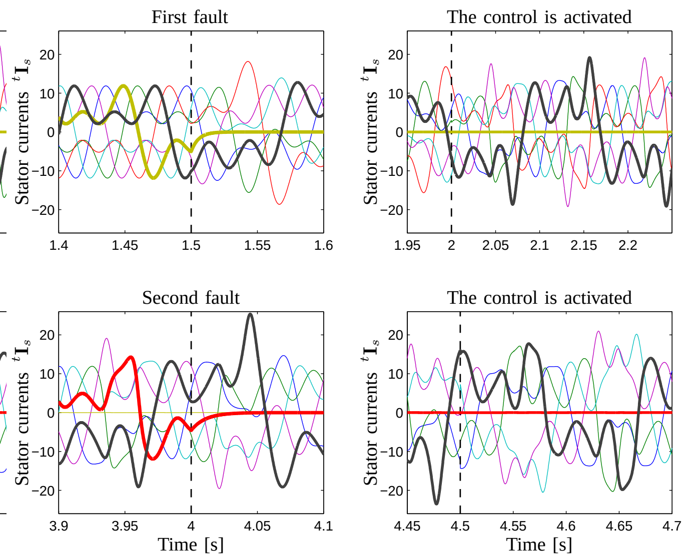

Fig. 8. Stator currents $^{t}\mathbf{I}_s$ in the fixed reference frame obtained using the control law described in Sec. III-B .

open phases but the control is not modified respect the first failure case. At time t_4 the fault tolerant control is applied and the torque grows again to the desired value $\tau_d = 30$ Nm without ripple. The different dynamic behavior of the motor torque and the motor velocity between the two fault tolerant controls is due to the two different control schemes (hysteresis for the first one and feed-forward action and a controller for the second one). However both the proposed fault tolerant controls ensure a constant torque without ripple.
Note that the symmetry of the healthy-phase currents with respect to the location of the faulty phases.

Additional mathematical details and more simulation results will be given in the final version of the paper.

V. Conclusion

In this paper the control of multi-phase permanent magnet synchronous motors under open-phase fault condition has been investigated. The proposed control laws ensure a constant torque without ripple under open-phase faults without any additional hardware. The proposed control laws are suitable for motors with a generic number of phases and in presence of one or more phase failures. The use of the POG modeling technique allows a direct implementation of the control in Simulink. Some simulation results show the effectiveness of the proposed model in the case of two non adjacent open phases of a 7-phase motor.

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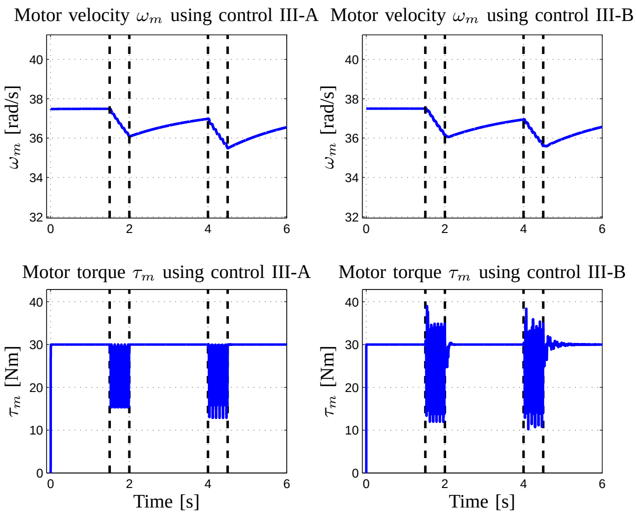

Fig. 9. Motor velocity ω_m and motor torque τ_m.

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