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Generation of On-line Optimal Current References for Multi-phase Permanent Magnet Machines with Open-circuited Phases

X. Kestelyn, E. Semail and Y.Crévits

Arts et Métiers ParisTech, L2EP, CER de Lille, Bd Louis XIV, 59046 Lille, France
Univ Lille Nord de France, F-59000 Lille, France

Abstract- **This paper deals with the generation of optimal current references for Multi-phase Permanent Magnet Machines with open-circuited phases. Compared to classical methods, the use of a vectorial approach makes it possible to generate optimal current references, from a copper losses point of view, on-line. This method is viable whatever the number of open-circuited phases. As an example, a five-phase machine is experimentally controlled.**

I. INTRODUCTION

Many applications require fault-tolerant drives in order to ensure continuing security or productivity. Among existing solutions, multi-phase drives offer, due to their inherent additional degrees of freedom, a good alternative [1][2]. For example, a wye-coupled n-phase machine can run with up to *n*-3 phases in fault-condition with no additional devices.

If many types of faults can occur, open-circuit faults are the most commonly found. In that case, currents in the healthy phases must be modified in order to reduce the impact of the fault on the torque quality. Several post-fault strategies may be applied. In most of the cases the objective is to keep a constant torque even with open-circuited phases. The limiting factor is then the thermal state of the machine, which is directly related to the level of the Joule losses.

Three sets of methods can be distinguished.

In the first set, the aim is to control currents in the remaining phases in order to keep balanced currents (i.e. with identical shape and amplitude) [3][4][5][6][7]. By doing this, each phase has the same Joule losses and, for some particular phase arrangements, the thermal behavior of the machine is controlled.

In the second set of existing strategies, the global Joule losses (i.e. generated by all remaining phases) are limited to a predefined value. Currents are unbalanced, but a global minimum of Joule losses can be reached [6][8][9].

In the two previous sets, hysteresis current controllers are used in order to follow complex and varying waveforms of currents in stator reference frame.

In the third set, simple current waveforms (1st harmonic or 1st and 3rd harmonics) are imposed [6][10][11] but their amplitudes are not imposed to be the same in healthy phases: with such simple current waveforms, the current references in each dq frame are constant in steady state; thus constant torque can be reach, by using PI controllers in each *dq* frame of the machine, on condition that electromotive forces are sinusoidal in each *dq* frame [12].

A common point between the methods found in the literature is that off-line calculations of current references are necessary.

First set methods consists in imposing the current waveforms of remaining phases and finding the best phase displacement of each current in order to obtain a constant torque [3][4][5]. Calculations are then reduced to the resolution of a system consisting of a number of equations equal to the number of unknowns (which are the phase displacements). Even if this class of strategies is well suited for machines with sinusoidal winding distribution and imposed sinusoidal currents, calculations become rapidly complex when several harmonics of winding distribution have to be taken into consideration. Paper [6] shows that harmonics of winding distribution can lead to a 4th order harmonic torque even if sinusoidal currents are imposed. Moreover, when these methods have been adapted to currents with a third harmonic component, torque pulsations have been observed [13]. Finally, it must be remarked that even if Joule losses are the same in each of the healthy phases, the temperature in their windings are not systematically the same since the temperature depends on the neighboring phases, which can be open-circuited or not.

Second set methods are based on global Joule losses minimization. This approach often leads to systems composed of more unknowns than equations. Then in order to solve these, techniques of optimization are required. Due to the time needed to obtain the solutions, on-line computation is prohibited [8][9].

Finally, third set methods demands to compute off-line new current references in order to adapt the number of degrees of freedom of the current vector to the number of degrees of freedom of the drive in fault-condition [11].

This paper proposes a novel way to generate on-line optimal current references in order to obtain a constant torque whatever the number of open-circuited phases of a n-phase Permanent Magnet Synchronous Machine (PMSM). Based on a vectorial approach [14], the proposed technique adapts naturally the dimension of the current vector according to the dimension of the accessible back-electromotive force (number of degrees of freedom adaptation). Minimization of global Joule losses is chosen as a criterion.

The paper is organized as follows. Section II gives the fundamental mathematical derivations making possible to understand the basics of the proposed method. Section III details the on-line generation of optimal current references in

order to keep a constant torque while minimizing global Joule losses.

In section IV, on-line generation of optimal current references is exposed using a five-phase PMSM. Finally, section V shows experimental results to prove the effectiveness of the method.

II. MATHEMATICAL DERIVATIONS

A n-phase Permanent Magnet Synchronous Machine (PMSM) can be modelled using (1):

$$\vec{v} = R\vec{i} + \ell\left(\frac{d\vec{i}}{dt}\right) + \vec{e} \tag{1}$$

$\vec{v}$, $\vec{i}$ and $\vec{e}$ are voltage, current and back electromotive force n-dimensional vectors. For example, $\vec{v}$ is expressed by $\vec{v} = \sum_{k=1}^{n} v_k \vec{x}_k$, with v_k the voltage across phase number k and $\vec{x}_k$ one of the n orthonormal vectors composing an orthonormal basis. ℓ is a linear application represented by an n-by-n inductance matrix.

Torque T is expressed by (2), with $\vec{\varepsilon}$ the speed normalized back electromotive force vector:

$$T = \frac{\vec{e}.\vec{i}}{\Omega} = \vec{\varepsilon}.\vec{i} \tag{2}$$

From the control point of view, for a given torque reference T^*, the generation of current reference vector $\vec{i}^*$ is imposed by (3):

$$\vec{i}^* = \vec{c}.T^* \tag{3}$$

with $\vec{c}$ a criterion making it possible the generation of a vector $\vec{i}^*$ from a scalar T^*.

To illustrate the previous equations (1), (2) and (3), Fig.1 shows a representation of the system (orange upper symbols) and its torque control (lower blue symbols) according to the Energetic Macroscopic Representation (EMR) formalism [15][16].
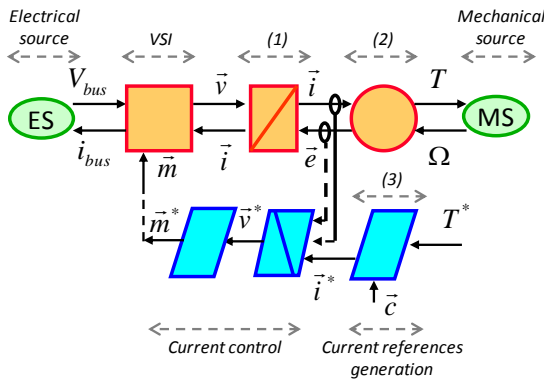

Figure 1. Representation of the system (upper orange symbols) and its torque control (lower blue symbols) according to the Energetic Macroscopic Representation (EMR) formalism

Criterion $\vec{c}$ can be computed according to several constraints. Among the most considered methods, one can cite strategies with balanced sinusoidal currents [5][6][7] and strategies with minimum copper losses [8][9]. A common point of all existing methods in the literature is that current references are computed off-line: in steady states the computed current waveforms, stored in memory, are imposed to feedback controller as references. In this paper, we develop an on-line method which is exposed in the next section.

III. ON LINE COMPUTATION OF AN OPTIMAL CRITERION

A. Minimum Joule losses criteria

This paper develops the minimization of instantaneous stator copper losses for a given torque expressed by (4):

$$p_J(t) = \sum_{k=1}^{n} Ri_k^2 = R\|\vec{i}\|^2 \min \tag{4}$$

For a given torque T, $\|\vec{i}\|$ norm is minimal if the scalar product $\vec{\varepsilon}.\vec{i}$ on the right hand of (2) is maximized, i.e. if $\vec{i}$ is collinear with $\vec{\varepsilon}$:

$$\vec{i}^* = A.\vec{\varepsilon}, \ A \ real \tag{5}$$

Substituting (5) in (2), it comes:

$$A = \frac{T}{\|\vec{\varepsilon}\|^2} \tag{6}$$

Using (3), it is possible to express criterion $\vec{c}$ as (7):

$$\vec{c} = \frac{\vec{\varepsilon}}{\|\vec{\varepsilon}\|^2} \tag{7}$$

It is fundamental to note that (7) gives a unique solution for determining $\vec{c}$. Consequently there is no need for techniques of optimisation to determine criterion $\vec{c}$. Then, compared to methods found in the literature, knowing the speed normalized back-electromotive force, (7) makes it possible to compute current references in real-time (on-line).

Moreover, since no assumptions were made concerning the number of phases, the inductance matrix or the back-electromotive force shape, (7) can be used for deducing current references of PMSM machines whatever the number of phases, open-circuited or not.

B. Joule losses expression

Using (3) and (7), (4) can be expressed by:

$$p_J(t) = \frac{RT^{*2}}{\|\vec{\varepsilon}\|^2} \tag{8}$$

For a constant torque reference T^*, the mean value of instantaneous Joule losses are expressed by (9) ($\langle x(t)\rangle$ is the mean value of $x(t)$):

$$P_J = RT^{*2}\left\langle \frac{1}{\|\vec{\varepsilon}\|^2}\right\rangle \qquad (9)$$

(9) can be also rewritten using (10):

$$T^* = \sqrt{\left\langle \frac{1}{\|\vec{\varepsilon}\|^2}\right\rangle^{-1} \frac{P_J}{R}} \qquad (10)$$

(9) can be used to evaluate the mean value of the Joule losses in normal or open-circuited phase mode under optimal control and (10) makes it possible to predetermine the maximum torque that the machine can provided for a given mean value of Joule losses.

IV. OPTIMAL CONTROL OF A FIVE-PHASE DC BRUSHLESS MACHINE IN NORMAL AND OPEN-CIRCUITED CONDITIONS

The computation of optimal references in normal and open-circuited mode is exposed in this section using a five-phase PMSM with trapezoidal EMF as an example. Table 1 gives the nine first harmonics of the speed normalized back-electromotive force ε of the machine considered on the paper.

TABLE I
NINE FIRST HARMONICS OF THE SPEED NORMALIZED BACK EMF

Harmonic rank	1	3	5	7	9
Amplitude (mV/rad/s)	320	91	40	16	5.3

The machine has two pole pairs, a rated torque of 5 N.m and a stator resistance $R=2.24\Omega$.

A. Normal mode (The five phases are connected to the VSI)

In this mode, since the machine is wye-connected, currents cannot contain zero-sequence components (fifth harmonic and multiples). Current vector $\vec{i}$ is then a n-1 dimensional vector.

In order to fulfil (5), the accessible EMF vector must be restricted to the same subspace as the current vector. Then, accessible EMF vector $\vec{\varepsilon}_{acc}$ is computed using (11):

$$\vec{\varepsilon}_{acc} = \vec{\varepsilon} - \vec{\varepsilon}_z \qquad (11)$$

with: $\vec{\varepsilon}_z = \left(\dfrac{\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 + \varepsilon_5}{\sqrt{5}}\right)\cdot\left(\dfrac{\vec{x}_1 + \vec{x}_2 + \vec{x}_3 + \vec{x}_4 + \vec{x}_5}{\sqrt{5}}\right)$

the zero-sequence component of $\vec{\varepsilon}$.

Criteria A and $\vec{c}$ are finally computed according to (12):

$$A = \frac{T^*}{\|\vec{\varepsilon}_{acc}\|^2} \qquad \vec{c} = \frac{\vec{\varepsilon}_{acc}}{\|\vec{\varepsilon}_{acc}\|^2} \qquad (12)$$

It must be noticed that if the number of first harmonics of $\vec{\varepsilon}$ is strictly inferior to the number of machine phases n, $\|\vec{\varepsilon}_{acc}\|^2$ is constant and current references have the same harmonic content than the electromotive forces.

For the considered machine this it is not the case since the nine first harmonics of speed normalized back-electromotive force ε are considered and the machine has five phases. Then, $\|\vec{\varepsilon}_{acc}\|^2$ is not constant and the spectral content of current references is more important than the spectral content of back-electromotive forces.

Fig. 2 shows the optimal current references and Fig. 6 the criterion A for a reference torque of 2N.m. both in normal mode. For this reference torque and according to (9), Joule losses are estimated at 32.3W.

B. Open-circuited phase mode (one or two phases are disconnected)

The accessible EMF vector is computed according to the open-circuited phases. For example, if phases 1 and 3 are open-circuited, accessible EMF vector becomes the *(n-3)*-dimensional vector:

$$\vec{\varepsilon}_{acc} = \vec{\varepsilon} - \vec{\varepsilon}_z - \vec{\varepsilon}_{13} \qquad (13)$$

with: $\vec{\varepsilon}_{13} = \varepsilon_1.\vec{x}_1 + \varepsilon_3\vec{x}_3$

and: $\vec{\varepsilon}_z = \left(\dfrac{\varepsilon_2 + \varepsilon_4 + \varepsilon_5}{\sqrt{3}}\right)\left(\dfrac{\vec{x}_2 + \vec{x}_4 + \vec{x}_5}{\sqrt{3}}\right)$

Criteria A and $\vec{c}$ are computed according to (12).

Fig. 3 to 5 show the optimal current references obtained for several configurations: one, two non-adjacent and two adjacent open-circuited phases when the torque reference is set to 2N.m. Fig. 6 and 7 show criterion A for each of these three cases.

For each functioning mode and keeping a torque reference of 2N.m, the Joule losses, according to (9), are the following:
- One phase: 44W (i.e. +36% compared to the normal mode)
- Two non-adjacent phases: 58W (i.e. +79.6%)
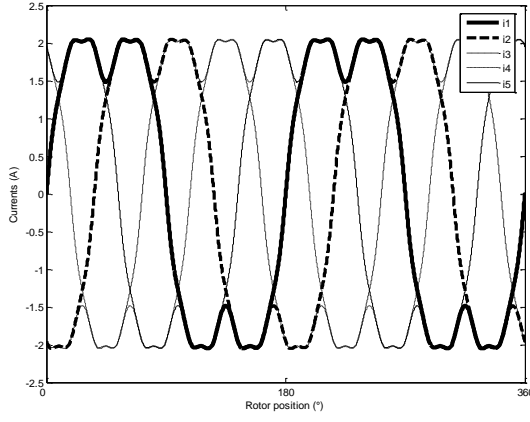- Two-adjacent phases: 641W (i.e. +1884%)

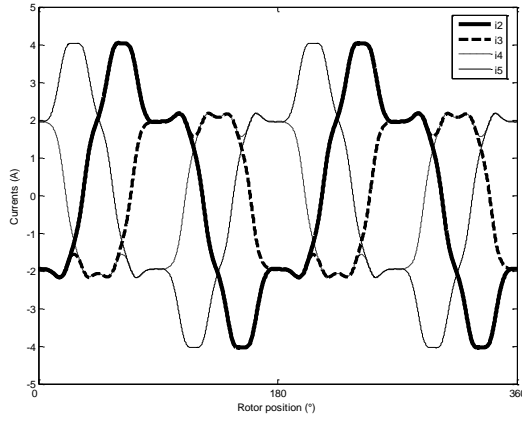Figure 2. Optimal current references in normal mode

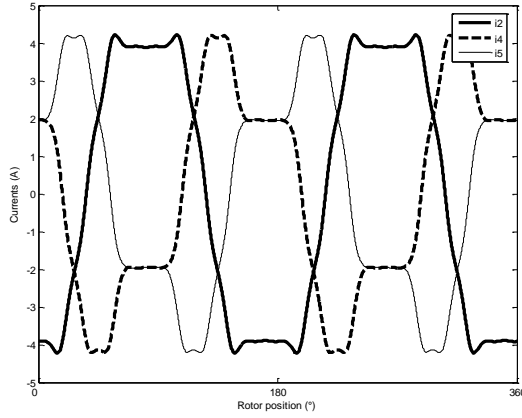Figure 3. Optimal current references with one phase open-circuited

Figure 4. Optimal current references with two non-adjacent phases open-circuited
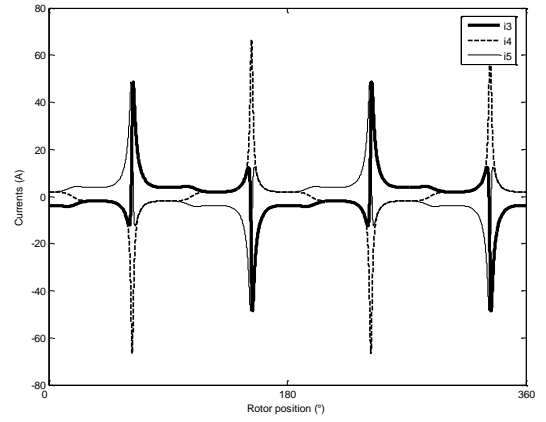

Figure 5. Optimal current references with two adjacent phases open-circuited
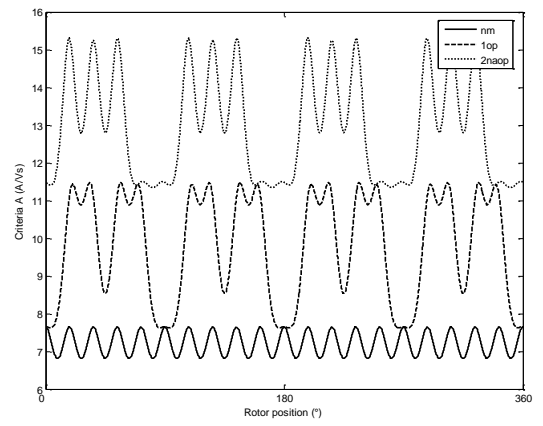

Figure 6. Criteria *A* for the normal mode (nm), one open-circuited phase (1po) and two non-adjacent open-circuited phases (2naop)
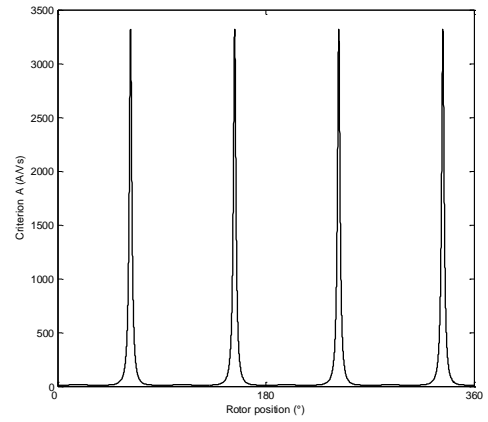

Figure 7. Criterion A for two adjacent open-circuited phases

Whatever the functioning mode, if the Joule losses have to be kept the same as in the normal mode (i.e. 32.3W), the torque reference has to be reduced in order to fulfil (10):
  − One phase: 1.71 Nm (i.e. -14.5%)
  − Two non-adjacent phases: 1.49 Nm (-25.5%)
  − Two-adjacent phases: 0.449 Nm (-77.6%)

C. Comparison with equivalent methods

The current references obtained by the proposed on-line method have similar waveforms to those obtained via off-line optimization with the Lagrangian approach exposed in [9]. However, compared to [9], the proposed method has several advantages: the references are computed on-line and there is a

direct link between the expected torque, the functioning mode and Joule losses. Finally, the harmonic content of current references can be mathematically computed in order to choose the best suited current controller.

V. EXPERIMENTAL IMPLEMENTATION

The optimal on-line control technique has been implemented on a wye-connected four-pole five-phase DC Brushless machine with trapezoidal EMF supplied by a 5-leg Voltage Source Inverter (VSI). The load torque is generated by a magnetic powder brake associated to an inertial load. A torquemeter SCAIME DR2513 is installed between the motor and the load in order to measure the mechanical torque. Fig. 8 gives a snapshot of the experimental test-bed.

Fig.9 shows the control structure of the experimental test-bed. The speed is estimated from the rotor position measured by a synchro-resolver and is regulated using a PI controller. The speed controller generates the torque reference. The optimal current reference generator generates on-line the current references according to (5) and (6) and the fault info which depends on the number of open-circuited phases.

For all tests, the DC Bus voltage has been set to 100V DC, the speed reference to 20 rad/s and the load torque to 2N.m. Since current references have complex shapes, currents are controlled using a hysteresis control whose bandwidth is sufficient.

The overall system is controlled by a DS1005 controller board from DSpace®.

To show the effectiveness of the proposed method, several tests under various configurations have been carried out. As an example, Fig.10 shows experimental currents when phase 1 is open-circuited and optimal current references are generated. In Fig.11, one can see the improvement of the torque quality when phase 1 is open-circuited. Keeping the same references as in normal mode (See Fig. 2) leads to a torque with harmonic of high amplitude. Using the optimal current references (see Fig.3) makes it possible to have a smoother torque as in normal mode.

VI. CONCLUSION

It is shown how a vectorial approach simplifies the determination of optimal current references regarding the minimization of stator copper losses. As a direct benefit, it has been experimentally proven that it is possible to achieve on-line calculation of the references.

Further studies are in progress to show that the vectorial approach can be used to compute optimal references according to other criteria.
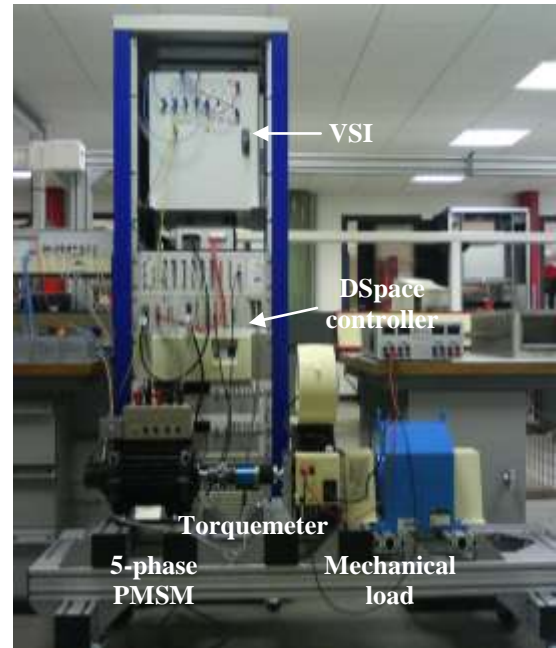

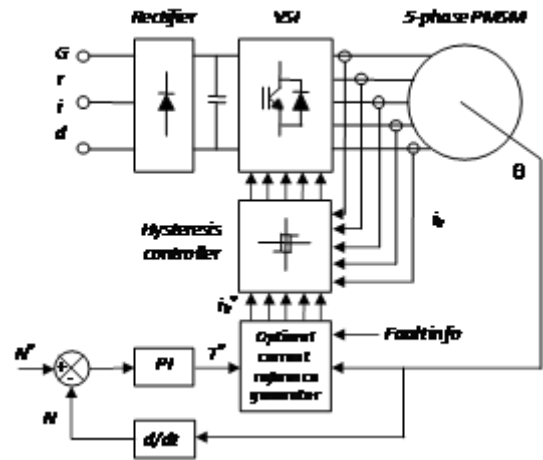Figure 8. Snapshot of the experimental test-bed.

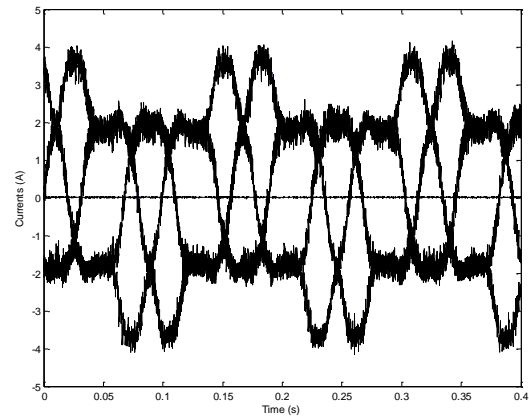Figure 9. Control structure of the experimental test-bed.

Figure 10. Experimental currents with phase 1 open-circuited and optimal current references.
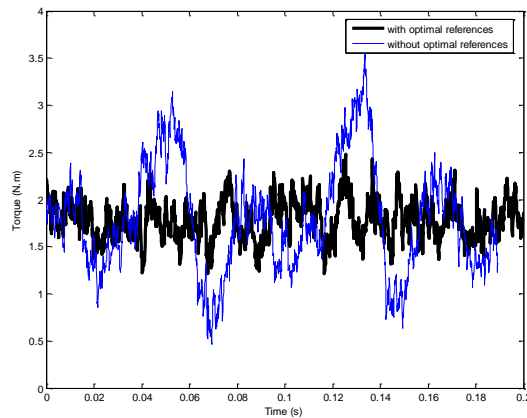
Figure 11. Experimental measured torques with and without optimal current references.

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