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Fault tolerant multiphase electrical drives: the impact of design

E. Semail, X. Kestelyn ^a, and F. Locment

L2EP ENSAM, 8 Bd Louis XIV, Lille 59046, France

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Abstract. This paper deals with fault tolerant multiphase electrical drives. The quality of the torque of vector-controlled Permanent Magnet (PM) Synchronous Machine supplied by a multi-leg Voltage Source Inverter (VSI) is examined in normal operation and when one or two phases are open-circuited. It is then deduced that a seven-phase machine is a good compromise allowing high torque-to-volume density and easy control with smooth torque in fault operation. Experimental results confirm the predicted characteristics.

PACS. 84.50.+d Electric motors - 07.10.Pz Instruments for strain, force, and torque

1 **1 Introduction**

2 Three-phase Wye-connected machines supplied by VSI are 3 the most common electrical drives. However, the tolerance 4 to the loss of one or two phases, due to the failure of power 5 devices of the VSI, is very low since there are only two in-6 dependent currents. Various configurations to improve the 7 reliability of the drive, keeping the same number of phases, 8 have been studied [1,2]. A modification of the coupling 9 allows recovering one freedom-degree: three currents are 10 then independent. In any case, the original simplicity and 11 low cost of the 3-phase drive is lost.

12 Multiphase machines with more than three phases can 13 be then considered [3,4]. Even if a higher number of 14 connections is not well adapted for the reliability, these 15 drives are interesting because of their fault-tolerant ca-16 pability: they can continue to run even with one or two 17 open-circuited phases. Moreover, the drawback of a higher 18 price for these drives is not so obvious especially for low 19 voltage/high current applications such as on-board systems [5,6]. For these systems, the current per phase can 20 be so important that it is not possible to use only two 21 power devices to achieve one leg of the VSI. Parallel/series 22 transistor associations must be used [7,8]. In this case the 23 overall number of transistors can be finally lower with a 24 25 5-phase or a 7-phase machine than with a 3-phase machine. Moreover the impact of one transistor failure is less 26 27 critical with multi-phase machines since it is possible to loose one phase: the overrating is consequently lower and 28 a better thermal repartition of the transistors losses can 29 be imagined. 30

If the loss of one or two phases is not as critical for fivephase [9] or seven-phase [4] machines as for three-phase machines, an important second time-harmonic torque ripples can appear because of the interactions between the spatial harmonics of the electromotive forces (EMF) and magnetomotive forces (MMF) [10]. The reduction of these torque ripples is an important issue in fault operation. 37

Fault-tolerant controls of multiphase machines have 38 been studied in the recent years for PM five-phase ma-39 chines. One solution proposed in [11] for the problem of 40 torque ripples is to impose a sinusoidal EMF for the ma-41 chine. However, an interesting characteristic of the multi-42 phase machines is lost in this case: low torque pulsations 43 even with a trapezoidal EMF. This possibility is interest-44 ing since it allows at first to increase the torque density 45 and secondly to reduce the constraints for the designer of 46 the machine in terms of windings and permanent magnets 47 shape. 48

Other solutions [12,13] suggest changing the control 49 structure when a fault occurs. A new transformation matrix is then used and the currents control is achieved in 51 a new synchronous frame with Proportional Integral (PI) 52 controllers. However, the control is consequently rather 53 complex especially when a third harmonic exists. 54

In this paper, we show for n-phase PM synchronous 55 machines that it is possible, if the total number of phase 56 n is enough high, to keep a trapezoidal EMF and also 57 the same simple control structure as in normal operation. 58 Only a few current references have to be modified. The 59 approach is applied to a seven-phase machine in the cases 60 of one or two open-circuited phases. The simplicity of the 61 control relies on a design constraint of the 7-phase ma-62 chine: its EMFs must contain only three harmonics: the 63 first, the third and the seven ones. 64

In the first part of the paper, a characterization of multiphase machines torque is given. The origin of the torque ripples harmonics is exhibited and then a constraint on machine design, that is adapted for fault operation, is deduced. A control scheme in fault mode operation is presented. 70

^a e-mail: Xavier.Kestelyn@lille.ensam.fr

In the second part, experimental results are given for a vector-controlled 7-phase machine that contains mostly the three imposed harmonics [14,15]. The mechanical torque is analyzed: in normal operation, when two phases are open-circuited with keeping the original control and when two phases are open-circuited using the improved control.

8 2 Torque characterization of multiphase 9 machines and deduced constraint

10 It has been shown [16,17] that a wye-connected *n*-phase 11 machine with n = 2F + 1 is equivalent to a set of *F* two-12 phase fictitious machines which are magnetically indepen-13 dent. Each fictitious machine M_g is characterized by an 14 EMF, a resistance, an inductance and a family of $nh \pm g$ 15 odd harmonics $(1 \le g \le F)$. Torque *T* of the *n*-phase ma-16 chine is the sum of torques T_g of the F fictitious machines. 17

$$T = \sum_{g=1}^{g=F} T_g. \tag{1}$$

Thanks to this multi-machine characterization, it is possi-18 ble to show that the vector control of an n-phase machine 19 can be deduced easily by implementing several times the 20 d_q -frame vector control usually used for three-phase ma-21 chines [17]. To ensure a pulsating torque equal to zero, it 22 $nh \pm g$ is then sufficient that the EMF contains harmon-23 ics ranks lower than n. Indeed, according to the $nh \pm g$ 24 odd harmonics associated with each fictitious machine, 25 this condition ensures only one harmonic for each ficti-26 tious machine, i.e. each fictitous machine has a sinusoidal 27 EMF. For a three-phase machine, it is found that the real 28 machine can contain the first and third harmonics, i.e. 29 the only two-phase d_q fictitious machine has a sinusoidal 30 EMF. For a seven-phase machine the first, third, five and 31 seven harmonics are allowed. 32

Consequently it can be deduced that, if low torque ripples are required, the constraints on the harmonic EMF content are less important for the designer when the number n of phases increases.

However, when one or two phases are open-circuited in a *n*-phase machine rotating at speed $\Omega = \omega/p$, with *p* the number of pole pairs, large 2 Ω torque pulsations can appear when the d_q current references of the vector control are unchanged.

The calculus of new current references has been achieved for three-phase and five-phase machines controlled in the natural frame [11] and has led to quickly variable current references. The bandwidth of the current controllers must be large: hysteresis controllers are usually used [11] with the direct inconvenience of a large band spectrum (problems of EMC compliance).

When the third harmonic of EMF is chosen to be kept
in order to get a high torque-to-volume density, the calculi
are still more complex than with a sinusoidal EMF.

To solve this problem, [12,13] propose to use PI controllers in d_q frames. In these frames the time variations of the current references are slower and consequently PI 54 type controllers can be used. Then, a usual Pulse Width 55 Modulation with a fixed carrier frequency can be chosen. 56 However, in [12,13] the model in fault mode operation is 57 not the same as in normal operation. For each fault mode 58 operation a new structure of the model is chosen with 59 a new transformation matrix and new reference frames. 60 Consequently, the practical implementation of the control 61 is heavy. 62

We have searched to keep advantages of both previously described approaches: a unique model for normal and fault mode operations and PI controllers in d_q reference frames. However, this is only possible if design constraints are imposed to the multi-phase machine.

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One solution is the following: the EMF of K two-phase fictitious machines must be equal to zero. Number K is defined by the inequality: $2K \ge G, G$ being the number of phases that can be lost. As an example, if one or two phases are lost, only one fictitious machine must have an EMF equal to zero.

This result is based on a few ideas.

At first, we consider that, even if in fault operation with open-circuited phases some actual currents are physically set to zero, the machine remains physically unchanged. The same machine model can be kept but some calculated current references must be modified to take into account these physical constraints.

In a second point, the loss of one or two phases cor-81 responds to the loss of one or two freedom degrees. It is 82 then impossible to impose the currents in all two-phase fic-83 titious machines. Nevertheless, we consider that it is pos-84 sible to choose the fictitious machine whose currents will 85 not be controlled any more. If the EMFs of this machine 86 are equal to zero, then the torque produced by this ma-87 chine will be null even with non-controlled currents. Con-88 sequently, as supposing that the reference torques in the 89 other fictitious machines are constant, the overall torque 90 of the multiphase machine will be constant too. 91

It is possible now to examine the impact of the number 92 of phases when this approach is applied. In the case of 93 a three-phase machine there is no solution since there is 94 only one two-phase fictitious machine. In the case of a five-95 phase machine, as there are only two two-phase fictitious 96 machines, it remains only one fictitious machine whose 97 EMFs can be not equal to zero: M1 machine, associated 98 with the first harmonic, is then chosen. Consequently, the 99 third harmonic of the EMFs must be equal to zero. In fact, 100 the EMFs of the real machine must be sinusoidal that is 101 a severe constraint for the designer of the machine. 102

In the case of a seven-phase machine it remains two 103 fictitious machines whose EMFs are not equal to zero. It 104 is then interesting to choose M1 and M3 machines associ-105 ated with the first and the third harmonics. We can thus 106 deduce that $7h \pm 2$ harmonic components of M2 EMFs 107 must be equal to zero. The first two corresponding har-108 monics are the fifth and the ninth ones. The amplitude of 109 the ninth component is naturally weak. It is easy to sup-110 press the fifth component of the EMF spectrum by acting 111 either on the shape of the permanent magnets and/or on 112

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Fig. 1. Vector control in d_q frames of a 7-phase machine.



Fig. 2. Time and frequency characteristics of EMF.

the stator windings [21]. In most of the cases, due the large
dimensions of the machine and the low number of poles
pairs, the magnets shape can be easily adapted without
any problems of industrialization. So it can be concluded
that seven is the minimum number of phases which allows building a high torque-to-volume density fault toler-

7 ant machine without severe constraints on its design.

8 3 Principle of control in fault mode peration

9 We explicit in the following paragraph how it is possible,
10 with a seven-phase machine whose EMFs of M2 fictitious
11 machine are null, to ensure low torque ripples when one
12 or two phases are not supplied.

The control structure in fault operation with open-13 circuited phases is kept the same as in normal operation. 14 The same machine model is kept but some calculated cur-15 rent references must be modified to take into account 16 the physical constraints imposed by the open-circuited 17 phases. The vector control of the machine is presented 18 in Figure 1 [18]. We can recognize three times the same 19 kind of control as for a three-phase machine. Of course, a 20 Concordia matrix transformation C_7 extended to a seven-21 phase machine and three rotation matrixes whose angle is 22 characteristic of each fictitious machine must be consid-23 ered. 24

We take advantage of the fact that M2 EMFs are equal to zero. Consequently, its current references do not have a direct impact on the torque. In normal operation, these references are set to zero in order to minimize the copper losses. In fault operation, current references will be calculated in order to impose constant torques in machines M1



Fig. 3. Double rotor, toroidal winding machine (on the left) with detail of the rotor on the right.

and M3 whereas one or two currents are equal to zero in one or two phases. By this way, the control scheme is the same as in normal operation, including the use of PI controllers. Only M2 current references have to be changed in the "Repartition of reference torques" block (See Fig. 1). 35

As an example, when two phases shifted by $2\pi/7$ are open-circuited (phases A and B), currents have to verify equation (2) which allows imposing the same currents in M1 and M3 as in normal mode: 39

$$\begin{bmatrix} C_7 \end{bmatrix} \begin{bmatrix} 0 \\ I_{M1} \sin(\omega t) \\ -I_{M1} \cos(\omega t) \\ i_{M2x} \\ i_{M2\beta} \\ I_{M3} \sin(3 \omega t) \\ -I_{M3} \cos(3 \omega t) \end{bmatrix} = \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_D \\ i_E \\ i_F \\ i_G \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ i_C \\ i_D \\ i_E \\ i_F \\ -(i_B + i_D + i_E + i_F) \end{bmatrix}$$
(2)

The solution of equation (2) is:

$$\begin{pmatrix}
i_{M2x} = -I_{M1}\sin(\omega t) - I_{M3}\sin(3\omega t) \\
i_{M2\beta} = I_{M1}(0.802\cos(\omega t) - 0.868(\omega t)) \\
+I_{M3}(0.445\cos(3\omega t) + 0.696\sin(3\omega t))
\end{cases}$$
(3)

4 Experimental results with a fault tolerant axial-flux machine

The previous theory has been applied to a seven-phase 43 prototype whose harmonic spectrum is given in Figure 2. 44 We have tried to get the lowest value for M2 machine 45 EMF whose main harmonics are the fifth and ninth ones. 46

In general, the right harmonic spectrum of the syn-48 chronous multi-phase machine can be obtained by acting 49 either on the winding [19] or on the magnets shape. The 50 studied prototype [16] is an axial flux PM machine with 51 two external rotors and one internal stator with toroidal 52 windings (see Fig. 3). In the case of axial flux machines, 53 the physical constraints for making the windings are se-54 vere. There is an asymmetry relatively to the windings 55 since it is more difficult to insert the end-windings at the 56 inner radius than at the outside radius. It is difficult to 57 achieve windings with more than one slot per pole and per 58

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Fig. 4. Experimental mechanical torques.



Fig. 5. Theoretical and experimental currents of the M2 machine.

phase. Consequently, the spectrum of the EMFs must be
essentially controlled thanks to the shape of the magnets.
For the studied prototype, a 4/5 arc pole (see Fig. 3) allows cancelling the fifth harmonic of EMF. Of course, it
should be possible to control more precisely the harmonic
spectrum of the EMFs but with more complex shapes or
non-radial flux magnetic density [20].

The tests have been achieved at 275 rpm for an aver-8 age torque (20 Nm) equal to one third of the rating torque 9 (65 Nm). To simplify the analysis of the figures, only M110 fictitious machine is supplied $(I_{M1} = 3A, I_{M3} = 0)$. In 11 Figure 4, we observe the mechanical torque (measured 12 by a torque transducer) at first in normal mode (NM), 13 then with two open-circuited phases without modification 14 15 of the control (DM1) and finally with new M2 machine 16 current references (DM2). A large second harmonic pul-



Fig. 6. Effect of a fifth harmonic on the electromagnetic torque.



Fig. 7. FFT of electromagnetic torques.

sating torque appears for case DM1: about a peak-to-peak 17 variation of 70% of the rated torque. It results from the 18 interaction between the first harmonic of currents and the 19 third harmonic of EMF. For DM2 case, the references ob-20 tained by equation (3) are imposed to the PI controllers of 21 M2 machine and lead to ripples torque which amplitude 22 is of the same order (less than 6% of the rated torque) 23 as in normal mode (less than 3% of the rated torque). 24 In Figure 5, reference and experimental current vectors of 25 M2 machine in $\alpha\beta$ plane are given. In accordance with 26 equation (3), the reference vector follows an ellipse locus. 27 If globally, the experimental current vector tracks the ref-28 erence, an error exists. Consequently, currents in M1 and 29 M3 machines can not be perfectly constant and a little 30 torque ripple appears. However the reduction is signifi-31 cant. 32

In order to point out the impact of the fifth harmonic of 1 EMF, a simulation has been achieved with a seven-phase 2 machine for which we have only changed the waveform of 3 the EMF: a square waveform has been chosen with con-4 sequently a ratio of 20% between the fifth and the first 5 harmonics. 6

We can observe in Figure 6 by comparison of the curves 7 (circle and square pictograms) that the modification of 8 the current references has a good impact on the torque 9 ripples, even if the machine has a square EMF. It is due 10 to the fact that this strategy imposes a constant torque 11 12 in machines M1 and M3. Nevertheless, the effect of the 13 special machine design is obvious by comparison of the curves (square and diamond pictograms): a reduction of 14 the torque ripples can be noticed. 15

Figure 7 shows the effect of the EMF harmonic content 16 versus the electromagnetic torque ripples. Keeping the 17 initial control (without modification), the interaction be-18 tween the EMFs and currents leads to high second, fourth 19 and sixth torque harmonics. With the improved control 20 and a square EMF, the second harmonic disappears and 21 it remains mainly a fourth and a sixth harmonic. This is 22 mainly due to the fifth harmonic of EMF. Finally, with the 23 EMF of the presented machine, it remains only an eight 24 harmonic due to the interaction of the first harmonic of 25 current with the 26

5 Conclusion 27

In this paper, we have presented, thanks to an analysis 28 29 of the torque characteristics of the multiphase machines, 30 the harmonic constraints that allow verifying several 31 objectives: a third harmonic EMF component for high torque-to-volume density, a constant torque when one 32 or two phases are open-circuited, an unchanged struc-33 ture of the vector control. We have then considered a 34 seven-phase machine that verified the previous objectives. 35 Experimental results confirm that a simple modification of 36 the current references allows effectively working with two 37 open-circuited phases and very low torque ripples. More 38 generally, we have shown how a little modification on the 39 design of the machine makes easier the control in fault 40 mode operation. Of course, for a seven-phase machine, the 41 cancellation of the fifth harmonic of EMF leads to a slight 42 reduction of the torque to volume ratio (less than 5% in 43 our case in comparison with a theoretical square –wave 44 EMF machine). Finally, the best moment to switch be-45 tween current references in normal and fault mode has to 46 be studied in order to reduce the induced transient phe-47 48 nomena.

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