Article:

Ede, J.A., Atallah, K., Wang, J.B. et al. (1 more author) (2002) Effect of optimal torque control on rotor loss of fault-tolerant permanent-magnet brushless machines. IEEE Transactions on Magnetics, 38 (5 (par). pp. 3291-3293. ISSN 0018-9464

https://doi.org/10.1109/TMAG.2002.802294

Effect of Optimal Torque Control on Rotor Loss of Fault-Tolerant Permanent-Magnet Brushless Machines

Jason D. Ede, Kais Atallah, Jiabin Wang, and David Howe

***Abstract*—A faulted phase in fault-tolerant permanent-magnet brushless machine can result in significant torque ripple. However, this can be minimized by using an appropriate optimal torque control strategy. Inevitably, however, this results in significant time harmonics in the phase current waveforms, which when combined with inherently large space harmonics, can result in a significant eddy-current loss in the permanent magnets on the rotor. This paper describes the optimal torque control strategy which has been adopted, and discusses its effect on the eddy-current loss in the permanent magnets of four-, five-, and six-phase fault-tolerant machines.**

***Index Terms*—Brushless machines, eddy currents, losses.**

I. Introduction

FAULT-TOLERANT permanent-magnet brushless ac machine designs differ significantly from conventional brushless machines, in that their phase windings are essentially isolated magnetically, thermally and physically. Thus, their fault-tolerance is significantly higher, a major consideration for safety-critical aerospace applications, such as fuel pumps [1] and flight control surface actuators [2], as well as applications in other sectors. However, in such fault-tolerant machines, the stator magnetomotive force (MMF) has fewer poles than the rotor permanent magnets. Therefore, torque is produced by the interaction of the rotor permanent magnets with a higher order stator MMF harmonic. The fundamental and lower order MMF harmonics can then give rise to significant rotor eddy currents, which can be minimized by employing multiple magnet segments per pole [3]. Further, a faulted phase, open-circuit, or short-circuit can result in a large torque ripple, which can be minimized by adopting an appropriate torque control strategy [4], [5]. However, this often results in significant time harmonics in the phase current waveforms. When combined with the inherently large lower order stator MMF space harmonics, this can result in a significant increase in the rotor eddy-current loss.

The paper will describe the optimal torque control strategy, which the authors have adopted for fault-tolerant brushless machines, and its effect on the eddy-current loss in surface-mounted rotor permanent magnets, of representative four-, five-, and six-phase machine designs (Fig. 1).

Manuscript received February 14, 2002.

The authors are with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, U.K. (e-mail: k.atallah@sheffield.ac.uk.

Digital Object Identifier 10.1109/TMAG.2002.802294.

(a) (b) (c)

Fig. 1. Fault-tolerant permanent-magnet brushless machines. (a) Four-phase. (b) Five-phase. (c) Six-phase.

II. Optimal Torque Control

A fault on one phase of a fault-tolerant brushless machine can result in a large torque ripple, which depends on the type of fault, *viz.* open-circuit or short-circuit, and the output torque T_o. Optimal torque control aims at achieving a ripple-free electromagnetic torque under both healthy and faulted conditions with minimum stator copper loss. For a healthy m-phase machine

$$T_o = \sum_{j=1}^{m} K_j(t) I_j(t) = \text{ constant.} \quad (1)$$

For an m-phase machine in which phase k is faulted

$$T_o - T_f(t) = \sum_{j \neq k}^{m} K_j(t) I_j(t) = \text{ constant.} \quad (2)$$

In both cases, the copper loss is required to be as low as possible, i.e.,

$$R \sum_{j=1}^{m} I_j^2(t) = \text{ minimum} \quad (3)$$

where R is the phase winding resistance, and $K_j(t)$ and $I_j(t)$ are the instantaneous ratio of the phase electromotive force (EMF) to the rotor speed and the instantaneous phase current, respectively. $T_f(t)$ is the instantaneous torque developed by the faulted phase k. Thus

$$\begin{cases} T_f(t) = 0, & \text{for an open-circuit fault} \\ T_f(t) = K_k(t) I_k(t), & \text{for a short-circuit fault} \end{cases} \quad (4)$$

where $I_k(t)$ is the short-circuit current in phase k. The required current waveforms in the healthy phases are obtained by minimizing the augmented objective function $F(i_1 \ldots, i_j, \ldots, i_m, \lambda)$ with a Lagrange multiplier λ. Thus

$$F = \sum_{j=1}^{m} I_j^2 + \lambda \left(\sum_{j=1}^{m} K_j(t) I_j(t) - (T_o - T_f(t)) \right) \quad (5)$$

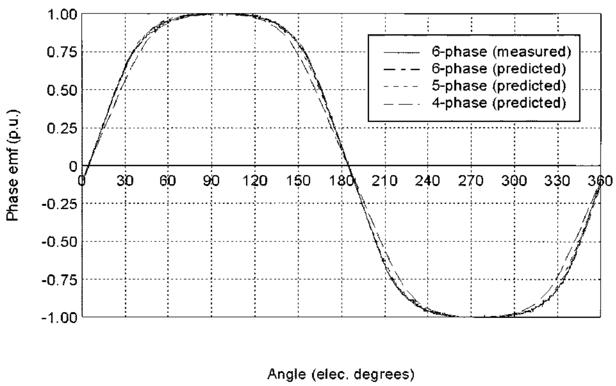

Fig. 2. Back-EMF waveforms.

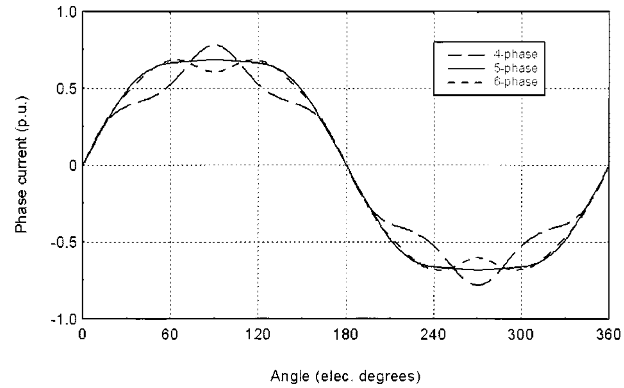

Fig. 3. Phase current waveforms. (As a per unit of the peak short-circuit current).

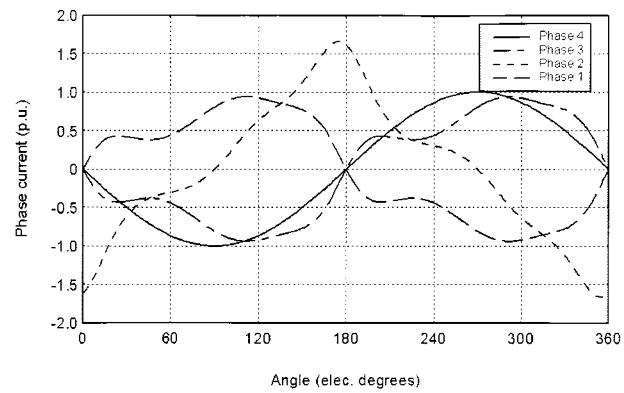

Fig. 4. Optimal phase current waveforms of four-phase machine when phase 4 is short-circuited. (As a per unit of the peak short-circuit current).

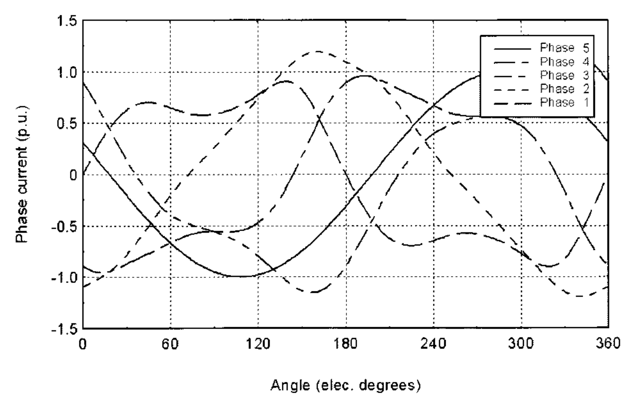

Fig. 5. Optimal phase current waveforms of five-phase machine when phase 5 is short-circuited. (As a per unit of the peak short-circuit current).

where, for an m-phase machine with a faulted phase $k, j \neq k$. The function F must satisfy

$$\frac{\partial F}{\partial I_j} = 0 \text{ and } \frac{\partial F}{\partial \lambda} = 0, \qquad j = 1, 2, \ldots, m. \tag{6}$$

Again, $j \neq k$ for a machine with a faulted phase k. Therefore, from (5) and (6), the instantaneous phase current waveforms in the healthy phases are given by

$$I_j(t) = \frac{K_j(t)\,(T_o - T_f(t))}{\left(\sum_{n=1}^{m} K_n^2(t)\right)} \tag{7}$$

where $n \neq k$, for a machine with faulted phase k. Further, in practice the magnitude of the instantaneous phase current is usually subject to a current limit $I_{\max}$. Depending on the demanded output electromagnetic torque T_o and the fault condition, the instantaneous current demands of s phases could exceed the current limit. In this case, the process of determining the optimal instantaneous currents may take several iterations. Therefore, if the instantaneous current demand of phase l exceeds the current limit, its current is clamped to

$$I_l(t) = \pm I_{\max} \tag{8}$$

where "$+$" applies if the current demand of phase l is positive, and "$-$" applies if it is negative. The torque contribution from the s phases is then given by

$$T(t) = I_{\max} \sum_{s} \pm K_l(t) \tag{9}$$

where "$+$" applies if the current demand of phase l is positive, and "$-$" applies if it is negative. The remaining phases are treated as a separate subset, and their current demands are determined by the same optimization method so as to satisfy the new torque demand $(T_o - T(t) - T_f(t))$. The new current demands are then given by

$$I_j(t) = \frac{K_j(t)}{\left(\sum_{n\neq k\neq l}^{m} K_n^2(t)\right)}\,(T_o - T(t) - T_f(t)), \quad j \neq k \neq l. \tag{10}$$

Again, the new current demands $I_j(t)$ are checked to ensure that none exceeds the specified current limit. If, however, the current demand of one or more phases from the new subset exceeds the current limit, the process is repeated until all the current demands satisfy the current limit constraint.

Fig. 2 shows the back-EMF waveforms of the four-, five-, and six-phase machines shown in Fig. 1, whilst Fig. 3 shows the phase current waveforms, which are required to produce ripple-free rated electromagnetic torque with minimum copper loss, when the machines are healthy. The associated copper losses are 0.96, 0.94, and 0.83 pu of the copper losses, which would result without optimal torque control (sinusoidal phase current waveforms). Figs. 4–6 show the phase current waveforms, which result in a ripple-free rated electromagnetic torque with minimum copper loss when a phase is short-circuited, for the four-, five-, and six-phase machines, respectively. It can be seen that for all machines the required peak phase current would exceed the peak short-circuit current, being >1.5 times the peak short-circuit current in the case of the four-phase machine. Further, Fig. 7 shows the variation of the copper loss with the mean electromagnetic torque when a phase is short-circuited,

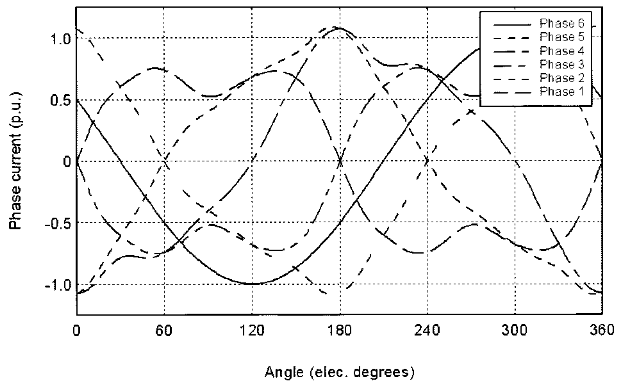

Fig. 6. Optimal phase current waveforms of six-phase machine when phase 6 is short-circuited. (As a per unit of the peak short-circuit current).

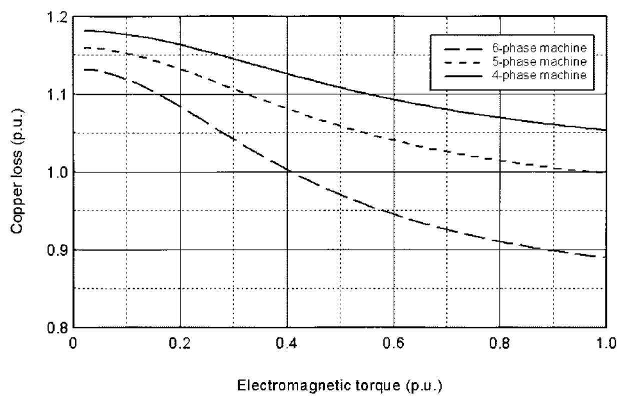

Fig. 7. Effect of optimal torque control on copper loss. (As a per unit of copper loss without optimal torque control).

TABLE I
EDDY-CURRENT LOSS IN ROTOR PERMANENT MAGNETS OF THE FOUR-PHASE MACHINE. (RATED ELECTROMAGNETIC TORQUE)

Control strategy	Current limit	Type of fault		
		No fault	Open-circuit	Short-circuit
Sinusoidal	No	1.00	1.30	1.67
Optimal torque control	No	1.00	1.66	2.20
	Yes	1.00	11.17	11.52

from which it can be seen that whilst the torque-ripple with a short-circuited phase winding can be eliminated by optimal torque control, this can result in a significant increase in stator winding copper loss. However, it should also be noted that the increase in copper loss should not compromise the thermal rating of the machines, since it is only about 0.05 pu at the rated electromagnetic torque, for the four-phase machine, which exhibits the highest increase in copper loss.

III. EDDY-CURRENT LOSS IN ROTOR PERMANENT MAGNETS

As will be evident, optimal torque control can result in relatively large time harmonics in the stator phase current waveforms, which when combined with stator MMF space harmonics could lead to a significant eddy-current loss in the rotor mounted permanent magnets. The four-, five-, and six-phase machines

TABLE II
EDDY-CURRENT LOSS IN ROTOR PERMANENT MAGNETS OF THE FIVE-PHASE MACHINE. (RATED ELECTROMAGNETIC TORQUE).

Control strategy	Current limit	Type of fault		
		No fault	Open-circuit	Short-circuit
Sinusoidal	No	1.00	1.25	1.52
Optimal torque control	No	1.05	1.40	1.87
	Yes	1.05	1.40	4.58

TABLE III
EDDY-CURRENT LOSS IN ROTOR PERMANENT MAGNETS OF THE SIX-PHASE MACHINE. (RATED ELECTROMAGNETIC TORQUE)

Control strategy	Current limit	Type of fault		
		No fault	Open-circuit	Short-circuit
Sinusoidal	No	1.00	1.27	1.52
Optimal torque control	No	1.10	1.38	1.74
	Yes	1.10	1.38	7.33

are equipped with sintered Sm_2Co_{17} permanent magnets, which have a relatively large electrical conductivity. The eddy-current loss in the magnets has been deduced from a series of two–dimensional (2-D) time-stepped, moving boundary, finite-element analyses, assuming the permanent magnets to be electrically conducting but to have zero remanence. Thus, they do not account for the eddy-current loss component, which would result from the variation of the magnet working point, due to the effect of stator slotting. Tables I-III show the effect of the type of fault and the stator current waveform/control strategy on the eddy-current loss of the permanent magnets, for the four-, five-, and six-phase machines, respectively. It can be seen that the eddy-current loss in the permanent magnets is influenced significantly by both the type of fault and the torque control strategy.

IV. CONCLUSION

An optimal torque control strategy for fault-tolerant permanent-magnet brushless machines has been presented. It has been shown that the adoption of a torque control strategy to minimize torque ripple under open-circuit and short-circuit fault conditions may lead to a significant increase in the eddy-current loss in the permanent magnets of such machines.

REFERENCES

[1] B. C. Mecrow, A. G. Jack, J. A. Haylock, and J. Coles, “Fault-tolerant permanent magnet machine drives,” in *IEE Proc. Elect. Power Applicat.*, vol. 143, 1996, pp. 437–442.
[2] K. Atallah and D. Howe, “Modular permanent magnet brushless machines for aerospace and automotive applications,” in *Proc. 20th Int. Workshop Rare-Earth Magnets and Their Applicat.*, Sendai, Japan, 2000, pp. 1039–1048.
[3] K. Atallah, D. Howe, P. H. Mellor, and D. A. Stone, “Rotor loss in permanent magnet brushless ac machines,” *IEEE Trans. Indust. Applicat.*, vol. 36, pp. 1612–1617, Nov.-Dec. 2000.
[4] T. Gobalarathnam, H. A. Toliyat, and J. C. Moreira, “Multi-phase fault-tolerant brushless DC motor drives,” in *Conf. Rec. IEEE Indust. Applicat. Conf.*, 2000, pp. 1683–1688.
[5] C. D. French, P. P. Acarnley, and A. G. Jack, “Optimal torque control of permanent magnet motors,” in *Proc. Int. Conf. Elect. Mach. ICEM’94*, pp. 720–725.