A Vector Controlled Axial-flux Seven-phase Machine in Fault Operation

F. Locment, E.Semail and X. Kestelyn

***Abstract*—This paper deals with control in fault operation of a seven-phase Axial Flux Permanent Magnet (AFPM) supplied by a seven-leg Voltage Source Inverter (VSI). We present a seven-phase machine that has been designed with a special ability to be controlled with only five phases supplied. Experimental results are provided when two phases are opened in two cases. In the first case, the vector control is not changed when two phases are opened: high torque ripples are then observed. In the second case, a specific control allows to reduce the torque ripples.**

***Index Terms*—Fault tolerant machine, vector control, Multiphase, axial flux machine.**

I. Introduction

THE 3-phase synchronous machines used for the low speed drives have usually sinusoidal back-electromotive forces (back-EMF) in order to minimize torque ripples thanks to a vector control. This implies constraints for the designer who must either acts on windings to realize a space filtering function or acts on the shape of permanent magnets. For axial flux machines whose windings are always simple because of technological constraints [1], this means special designs such as skewed slots, particular shapes or repartitions of permanent magnets [2], [3]. One solution is to use multiphase machines for which efficient vector-control can be implemented even with non-sinusoidal back-EMF [4], [5]. Smooth torque can be obtained without constraints on permanent magnets.

Besides, compactness of these AFPM machines makes them attractive for embedded applications such as traction, wind power generators [6], naval and submarine electrical propulsion. In these cases, reliability is interesting either in terms of security or of maintenance (for offshore wind power generator by example). Embedded systems require also generally low vibrations (low torque ripples). Multiphase AFPM machines can appear as an interesting solution.

Multiphase machines benefit of an intrinsic reliability. When one phase is opened it is still possible to maintain an average torque without change of the configuration of the power converter. However, undesirable low frequency torque ripple appear. In case of permanent magnet synchronous, there are a few studies on five-phase radial flux machines [7]-[9] but we know only one paper [10] with experimental results for a seven-phase radial flux machine. In [10], the back-EMF is trapezoidal but the control is not a vector control. At faulty condition, the control is based as in [9] on an algorithm developed for five-phase induction machines [11] keeping the stator magneto-motive force unchanged by modification of the currents. In [9], new references of current are also defined and control of these real currents is obtained by hysteresis type controllers with the well-known problem of variable frequency for the power components. In [12]-[13], torque is directly expressed and new currents are found in fault operation in order to keep constant the torque. The calculations are simple but each current of each phase must be determined and controllers have to follow variable references. In [7]-[8], new models are considered in fault operation and new vector control with PI-type controller are used since the references of the current are constant: it is rather complex since the transformations must be changed.

In this paper, a seven-phase with special harmonic spectrum of back-EMF has been designed in order to use a vector control which is the same in normal [5] and fault operation. PI controllers with Pulse Width Modulation (PWM) VSI at constant carrier frequency are sufficient to get a constant torque in fault operation. The design of this machine and its vector control is based on a multi-machine characterization of the multiphase machine. After a description of this modeling, the seven-phase machine is presented and characterized. Finally, experimental results of control of the machine in normal and fault operation show the effective ability of the machine.

II. Multi-machine vectorial characterization

Under assumptions of no saturation, no reluctance effects and regularity of design, a vectorial formalism allows to prove that a wye-coupled seven-phase machine is equivalent to a set of three magnetically independent fictitious 2-phase machines [5] named *M1*, *M2* and *M3*. Each equivalent machine is characterized by its inductance (resp. L_{M1}, L_{M2} and L_{M3}), resistance (resp. R_{M1}, R_{M2} and R_{M3}), and back-EMF (resp. $\overrightarrow{e_{M1}}$, $\overrightarrow{e_{M2}}$ and $\overrightarrow{e_{M3}}$). The torque of the real machine T is the sum of the torque of these three machines T_{M1}, T_{M2} and T_{M3}. The seven-leg VSI can also be decomposed into three fictitious VSI electrically coupled by a mathematical transformation Concordia's type [5]. A fictitious VSI is

Manuscript received June 30, 2006. This work is part of the project 'Futurelec2' within the 'Centre National de Recherche Technologique (CNRT) de Lille' with EDF and AREVA/Jeumont.
F. Locment, E.Semail and X. Kestelyn are with the L2EP, ENSAM, 8 Bd Louis XIV 59046 FRANCE, (e-mail: eric.semail@lille.ensam.fr).

specify a special characteristic in terms of harmonics of back-EMF: the amplitude of the 5th and 9th harmonics should be equal to zero. The machine has then a special feature that is used by the vector control in fault operation.

After prototyping with 3D-FEM for the sensitive predetermination of cogging torque and harmonics of back-EMF, the machine has been made and vector control tested. The results are in agreement with the simulations.

The presented control strategy is original since it is a vector control which keeps the same PI controllers in normal and in fault operations. A modification of the current references in a fictitious machine has only to be calculated to reduce drastically the torque ripples which appear when two phases are opened.

More generally, we can consider the number of phases of a machine as a parameter of design which can make possible the definition of simple structures from the technological point of view of the manufacturer. This approach can be extended to seven-phase radial flux machines but as it is not possible to shift the rotors to reduce the cogging torque a fractional-slot winding can be used as in [15].

REFERENCES

[1] M. Aydin, S. Huang and T. A. Lipo, "Axial Flux Permanent Magnet Disc Machines: A Review", *Proc. of EPE-PEMC'04*, Sept. 2004, Riga, Latvia, CD-ROM.

[2] A. Parvianen, M. Niemela and J. Pyrhonen, "Modeling of Axial Flux Permanent-Magnet Machines", *IEEE Trans. On Indus. Appl.*, Vol. 40, no. 5, Sept/oct 2004, pp 1333-1340.

[3] K. Rahman, N. Patel, T. Ward, J. Nagashima, F. Caricchi and F. Crescimbini, "Application of Direct Drive Wheel Motor for Fuel Cell Electric and Hybrid Electric Vehicle Propulsion System", *Proc. of IEEE-IAS'04*, Vol.3, pp. 1420 – 1426, Seattle (USA), Oct. 2004, CD-ROM.

[4] H-M Ryu, J-W Kim and S-K Sul, "Synchronous Frame Current Control of Multi-Phase Synchronous Motor, Part I. Modeling and Current Control Based on Multiple d-q Spaces Concept Under Balanced Condition", *Proc. of IEEE-IAS'04,* Vol. 1, pp. 56-63, Seattle (USA), Oct. 2004.

[5] E. Semail, X. Kestelyn, and A. Bouscayrol, "Right Harmonic Spectrum for the back-electromotive force of a n-phase synchronous motor", *Proc. of IEEE-IAS'04*, Vol. 1, pp.71-78*,* Seattle (USA), Oct. 2004.

[6] D. Vizireanu, X. Kestelyn, S. Brisset, P. Brochet, and E. Semail, "Experimental tests on a 9-phase Direct Drive PM Axial-Flux Synchronous Generator", *Proc. of ICEM'06,* Chania, (Greece), Sept. 2006, CD-ROM.

[7] H-M Ryu, J-H Kim and S-K Sul, "Synchronous Frame Current Control of Multi-Phase Synchronous Motor, Part II. Asymmetric Fault Condition due to Open Phases", *Proc. of IEEE-IAS'04*, Vol. 1, pp. 268-275, Seattle (USA), Oct. 2004.

[8] E. Robert-Dehault, M. F. Benkhoris and E. Semail, "Study of a 5-phases synchronous machine fed by PWM inverters under fault conditions", *Proc. of ICEM'02,* Brugge (Belgium), August 2002, CD-ROM.

[9] L. Parsa and H. A. Toliyat, "Fault-Tolerant Five-Phase Permanent Magnet Motor Drives", *Proc. of IEEE-IAS'04*, Vol.2, pp. 1048-1054, Seattle (USA), Oct. 2004.

[10] J. Figueroa, J. Cros, and P. Viarouge, "Polyphase PM brushless DC motor for high reliability application", *Proc. of EPE2003*, Toulouse (France), September 2003, CD-ROM.

[11] J-R Fu and T. A. Lipo, "Disturbance Free Operation of a Multiphase Current Regulated Motor Drive with an opened phase", *IEEE Trans. on Industry Applications*, Vol. 30, n°5, pp. 1267-1274, September/October 1994.

[12] J-P. Martin, F. Meibody-Tabar and B. Davat, "Multiple-phase Permanent Magnet Synchronous Machine Supplied By VSIs working under Fault Conditions", *Proc. of IEEE-IAS'001*, Vol.3, pp. 1710 - 1717 Roma (Italy), Oct. 2000, CD-ROM.

[13] W. Jiabin, K. Atallah, and D. Howe, "Optimal torque control of fault-tolerant permanent magnet brushless machines", *IEEE Trans. on Magnetics*, Vol. 39, Issue 5, pp. 2962-2964, Sept. 2003.

[14] F. Locment, E. Semail, F. Piriou, "Soft Magnetic Composite Axial Flux Seven-Phase Machine", *Proc. of ICEM'06,* Chania, (Greece), Sept. 2006, CD-ROM.

[15] F. Scuiller, J.F. Charpentier, E. Semail, S. Clenet, "A global design strategy for multiphase machine applied to the design of a 7-phase fractional slot concentrated winding PM machine", *Proc. of ICEM'06,* Chania, (Greece), Sept. 2006, CD-ROM.