A global design strategy for multiphase machine applied to the design of a 7-phase fractional slot concentrated winding PM machine

F. Sciuller, J.F. Charpentier, E. Semail and S. Clénet

Abstract—**This paper describes a global methodology of design for multiphase Permanent Magnet (PM) machines. Firstly a general multimachine theory for modeling multiphase machines is presented. This theory allows to define constraints and objectives for the design of PM machines supplied by Pulse Width Modulation Voltage Source Inverter (PWM VSI) and allows to define pertinent control strategies. The deduced machine design specifications are related to the association of converter with machine, the minimization of the torque ripple and the maximization of the compactness. An interesting way to reach these goals is to use non conventional winding strategies based on multiphase fractional slot windings. In this paper this methodology is illustrated by the modification of the design of an existing vehicle propulsion 3-phase machine into a 7-phase one with fractional slot concentrated windings. This new design allows to improve significantly the performances of the system in terms of torque ripple and torque density.**

Index Terms—**Multiphase machine, PM machine, torque ripples, torque density, design methodology.**

I. Introduction

ONE of the most required specifications for electrical PM machine supplied by PWM VSI is the compactness and the reduction of the torque ripples in order to improve the acoustic behavior of the machine. For 3-phase machines, sinusoidal electromotive forces allow low torque ripples thanks to vector control. But this constraint implies a particular winding and/or rotor design. For machines with higher phase number, low torque ripples can be obtained with non sinusoidal electromotive forces [1]. The strategy of design and control of high phase number PM machine can be deduced from a general multimachine modelling of multiphase machines. This general theory allows to define constraints and objectives for the machine design.

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A specific constraint, related to the machine-converter association is that the several characteristic time constants of a multi-phase machine must be large enough when a PWM VSI is used. We search also to reduce the torque ripples and increase the torque density. These goals can be reached by using non conventional winding solutions. The paper underlines the existence of efficient fractional slot multiphase concentrated windings, particularly suitable for small axial length machine. This kind of windings takes into account the design and drive constraints inherent to high phase number and allows to minimize the end windings. This solution allows to minimize the axial length and the copper losses related to the non active parts of the windings. To illustrate the described design strategy an existing hybrid vehicle propulsion 3-phase machine [2] is converted into a 7-phase one with fractional slot concentrated windings. The modification both reduces the ripples and improves significantly the torque density.

II. Multimachine Modeling of a Multi-phase Machine

A. Hypothesis and Notations

Usual assumptions are used to model the machine:

- the N phases of the machine are identical
- the N phases are regularly shifted
- effects of saturation and damper windings are neglected
- the electromotive force (EMF) in the stator windings is not disturbed by stator currents.

All quantities relating to the phase k are written x_k.

B. Usual Modeling in a Natural Base

In the usual matricial approach of N-phase electric machines, the machine is associated with an Euclidean vectorial space of dimension N noted E^N. This space is provided with the usual canonic dot product and with an orthonormal base $B^N = \left\{ \overrightarrow{x_1^N}, \overrightarrow{x_2^N}, ..., \overrightarrow{x_N^N} \right\}$ that can be called natural since the coordinates of a vector in this base are the measurable values relative to each phase.

In this natural base, useful vectors are defined:

- voltage vector $\vec{v} = v_1 \overrightarrow{x_1} + ... + v_N \overrightarrow{x_N}$
- current vector $\vec{i} = i_1 \overrightarrow{x_1} + ... + i_N \overrightarrow{x_N}$

The figure 3 depicts the two elementary EMF signals. The objective of a sine-wave for the 7-phase EMF is nearly reached.

The figure 4 describes the improvements concerning the torque that can be expected with the 7-phase machine. The torque is obtained by supposing a perfect sinusoidal current. So the presented calculations do not take into account the effects of the PWM VSI supply. With the new 7-phase machine, the pulsating torquesare drastically reduced. Furthermore, according to numerical predictions, the cogging torque is almost equal to zero thanks to the pertinent pole/slot combination. Concerning the torque density, with the same copper losses, *Pj0*, as the 3-phase machine (called "M3" on fig4.), the new machine (called "M7") provides a torque increased of 7 %. For the same torque value for the two machines, *Tm0*, the copper losses are reduced of about 12 % with the 7-phase motor.

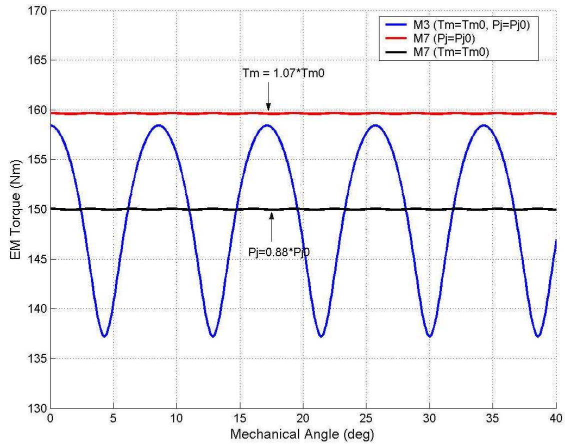

Fig. 4. Comparizon of the two EM torques produced by the reference and new machines with perfect sinusoidal current

The proposed 7-phase winding appears really efficient to improve the machine torque quality in term of density and ripples. Moreover, the range of the constant times of the fictitious machine is tight: the PWM frequency will not too high. However, these promising results must be moderated by the issue of the regularity of the stator magnetomotive force [11] (due to the magnetomotive force sub-harmonics). In fact, this MMF is less correctly distributed in the 7-phase machine than in the 3-phase one. Consequently, the potential resulting mechanical stresses will have to be estimated in order to determine if they are acceptable.

V. Conclusion

According to numerical simulations, the example discussed in the paper shows the improvements that the general multimachine based design methodology of multiphase machine presented in this paper can imply in terms of torque ripple minimization and torque density. The performance of an existing 3-phase hybrid vehicle motor is significantly improved by modification of the windings topology in order to obtain a 7-phase fractional slot concentrated winding. These results are all the more promising as they could be still better by an adaptation of the rotor geometry to make other fictitious machines able to provide torque. So further studies are considered to illustrate this statement. For example, if the EMF contains a significant part of harmonic 3, the torque density can be increased by supplying the second fictitious machine with third current harmonic injection. In adition, it will be interesting to fully assess the influence of the PMW VSI supply and the influence of the MMF distribution.

References

[1] F. Scuiller, E. Semail, J.F. Charpentier, S. Clénet, "Comparison of conventional and unconventional 5-phase PM motor structures for naval application system", IASME Transactions, Issue 2, vol.1, April 2004, pp.365-370.

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

[3] Figueroa J. Cros J. and Viarouge P. , "Generalized Transformations for Polyphase Phase Modulation Motor", *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, June 2006

[4] Kestelyn X., Semail E., Hautier J.P., "Vectorial Multi-machine modeling for a five-phase machine", *proceedings of ICEM 02*, 25-28 August 2002, Bruges, Belgium.

[5] F. Scuiller, J.F. Charpentier, E. Semail, S. Clénet, "A multi-phase surface mounted permanent magnet design to reduce torque ripples and Joule losses for Naval applications", in the proceedings of the All Electrical Ship symposium (AES 2005), 13-14 October 2005, Versailles, France, CD-ROM.

[6] Cros J. and Viarouge P., "Synthesis of High Performance PM Motors With Concentrated Windings", *IEEE Transactions on Energy Conversion*, vol. 17, no. 2, June 2002

[7] G. Hennemberg and al. Influence of end windings leakage in PM excited synchronous machine with asymmetrical rotor design", 6th International Conference on Electrical machines and Drives pp 305-311, IEE , sept 1993

[8] Zhu Z.Q., Howe D. "Influence of Design Parameters on Cogging Torque in Permanent Magnets Machine", *IEEE Transactions on Energy Conversion*, vol.15, no.4, December 2000.

[9] Magnussen F., Thelin P., Sadarangani C., "Performance Evaluation of PM synchronous machines with concentrated and distributed Windings including the Effects of Field-weakening", *proceedings of the IEE Second PEMD*, 31 March – 2 April 2004, Edinburgh, UK.

[10] M. Lajoie-Mazenc, H. Hector, R. Carlson, "Procédé d'analyse des champs électrostatiques et magnétostatiques dans les structures planes et de révolution : programme DIFIMEDI", Compumag'78, Grenoble France 4-6 sept. 1978.

[11] F. Magnussen, D. Svechkarenko, P. Thelin, C. Sadarangani, "Analysis of a PM machine with Concentrated fractional pitch windings", in the proceedings of the Nordic Worshop on Power and Industrial Electronics (NORPIE), Trondheim, Norway, 14-16 June 2004

[12] E. Semail, X. Kestelyn, A. Bouscayrol, "Sensitivity of a 5-phase Brushless DC machine to the 7th harmonic of the back-electromotive force", *Proc. of IEEE-PESC'04,* Aachen (Germany), June 2004, CD-ROM.

[13] Figueroa J. Cros J. and Viarouge P. , "Cuurent Control Strategies for Seven Phase brushless DC Motors", *proceedings of ICEM 02*, 25-28 August 2002, Bruges, Belgium.