Comparison of two 5-phase Permanent Magnet machine winding configurations. Application on naval propulsion specifications.

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***Abstract*— This paper describes a design approach dedicated to multiphase Surface Mounted Permanent Magnet SMPM machines. Based on a vectorial multimachine modelling that splits the multiphase machine in a set of magnetically independent fictitious machines, this approach allows to determine a pertinent control topology in case of Pulse Width Modulation (PWM) Voltage Source Inverter (VSI) supply. Design rules to reduce the parasitic currents and the torque ripples can also be deduced. This method is applied to improve the adaptation of a naval propulsion PM 5-phase machine to its converter. From a classical initial design with fully-pitched concentrated winding, the machine is improved by performing a new fractional-slot winding which drastically decreases the cogging torque. To make this winding possible, only the pole number has been modified (from 16 to 14). Iron, magnet and copper volumes are unchanged. For the two machines, a vector control to have sinusoidal currents is considered. For a same average torque, a decrease of the copper losses (less 35%) is observed mainly due to the reduction of parasitic currents. Furthermore a significant diminution (less 36%) of the torque ripples is obtained as a consequence of weakened interactions between the harmonics of the electromotive force and current. In comparizon with the full-pitched concentrated winding, the fractional-slot winding improves significantly the torque quality (better density and lower ripples) and makes the current control easier without over-sizing the electronic components.**

I. Introduction

Multi-phase motors are widely used in electrical marine propulsion for reasons as reliability, smooth torque and partition of power [1], [2]. Among the different kinds of multiphase motors, the synchronou PM one appears as an attractive solution to improve the compactness of the propulsion system. These multi-phase motors can now be supplied by a PWM VSI which increases the flexibility of the control. In order to take advantage of this attractive topology, efficient vector control laws must be defined [3], [4] but also adapted designs must be etablished [5]. It is possible to work on the shapes and the repartition of the magnets and on the windings. After usual windings with one slot per pole and per phase, windings with a fractional number of slots per pole and per phase begin to be examined [3], [6]. In this paper, from a reference 5-phase machine designed for a small-podded ship propeller, we make without changing the stator magnetic core a new 5-phase winding design that improves the compactness and reduces the torque ripples.

In section I, a vectorial multimachine model dedicated to SMPM machines is described. By cancelling the numerous electromagnetical couplings inherent to the multiphase machine, this tool allows to predict the behavior of the machine from rules linked with spatial harmonic interactions. The section II shows that this multimachine modeling is an appropriate way to define systematic design and control rules for SMPM multiphase machine supplied with PWM VSI. In the section III, the multimachine design rules are used to improve the adaptation of a 5-phase machine to its converter.

II. Multi-machine modelling of a multi-phase machine

A multiphase machine is difficult to study owing to its numerous inherent magnetical couplings. The multimachine modelling [7] enables a systematic study of this system with the particularity of taking into account the whole space harmonics.

A. Property of the stator inductance matrix

In this paper, only the case of odd phase number is considered. The multimachine approach needs the usual following assumptions:

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

According to these hypothesis, the inductance matrix M_{ss} that links the stator flux due to the stator with the voltage phase currents is symetric and circular. So it can be diagonalized by using a generalized *Concordia* transformation. This transformation makes $F = (N+1)/2$ eigenspaces that are orthogonal each other appear:

- the first eigenspace E_0, associated with eigenvalue λ_0, is a vectorial line

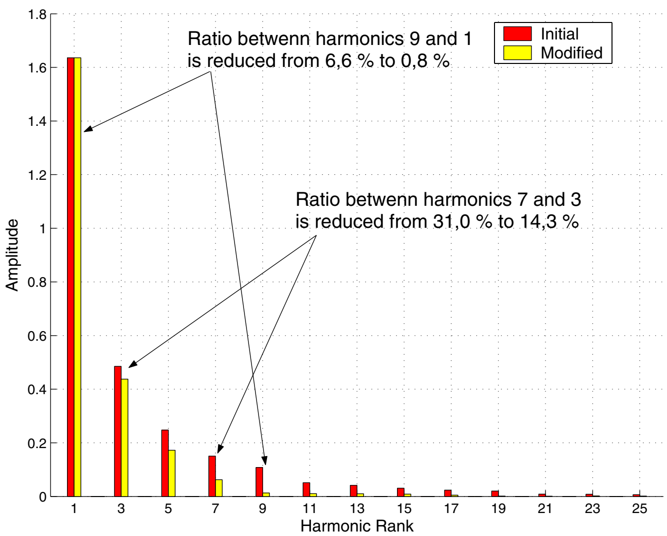
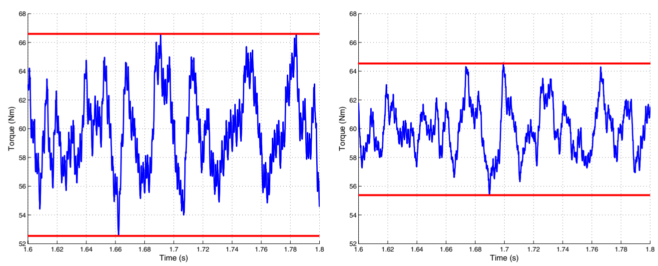


Fig. 6. Back-EMF spectrum of the two machines (at 1 rad/s)



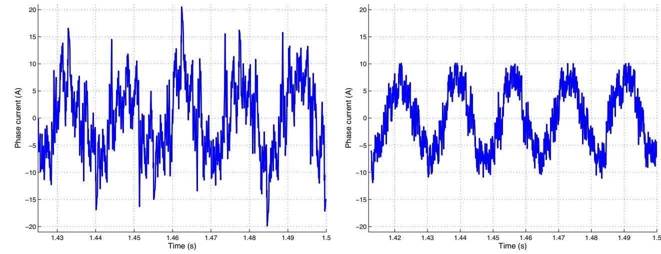
(a) Initial Machine (b) Modified Machine

Fig. 7. Comparizon of the torque produced by the two 5-phase motors for the same torque-speed point: 60 Nm @ 500 rpm

new machine, the amplitude of the parasitic currents are less important (as shown on the figure 8) and then the copper losses are reduced to 35%. This improvement is explained by the two following points: the new back-EMF is less disturbing and the new electrical time constants are more adapted to the PWM frequency.

V. Conclusion

The paper shows the torque quality improvements and copper losses reduction that can be expected if the PM multiphase machine is sized and controlled by considering the multimachine theory. In the case of a PWM VSI supply, the phase winding must be designed by taking into account the whole fictitious machine time constants in order to limit parasitic currents. As illustrated in this paper, the fractional slot windings are an efficient way to reach this goal without oversizing the electronic components. The expected 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. In the case of the 5-phase machine, if the back-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.



(a) Initial Machine (b) New Machine

Fig. 8. Comparison of the parasitic currents in the two machines

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