Predetermination of Currents and Field in Short-Circuit Voltage Operation for an Axial-Flux Permanent Magnet Machine

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Risk of irreversible magnet demagnetization during short-circuit fault is analyzed in case of an axial-flux dual-rotor machine, using a three-dimensional finite-element method (3D-FEM). In order to validate the numerical model, calculated waveforms of the currents are compared with experimental results for short-circuit at low speeds. Then currents and magnetic flux density inside the magnets are computed for short-circuit at higher speeds in order to predetermine the maximum admissible speed for the machine.

Index Terms — 3D Finite Element Method, Short-circuit fault, seven-phase machine, Axial Flux Permanent Magnet Machine, Soft Magnetic Composite.

I. Introduction

Fault tolerance of electrical machine is an important issue for embedded systems as offshore wind generators. Permanent Magnet machines with more than three phases are attractive [1][2]. Since they can still work with several open-circuited phases. However, it is also necessary to confirm their ability to withstand short-circuit fault currents without irreversible magnet demagnetization [3]. Besides, new material and geometrical constraints yields interest forward Axial Flux Permanent Magnet synchronous machines (AFPM) [4][5].

The paper tackles with the predetermination of short-circuit currents in a seven-phase AFPM generator with two external rotors and iron-powder stator core. Even if thermal effect of short-circuit current is acceptable, it is necessary to verify that, during the time between the occurrence of a short-circuit fault and the action of the overload protections, irreversible demagnetization of the magnet is not reached. Thus, determination of magnetic flux density inside the magnets is of great interest.

In section II, the small scale AFPM prototype, whose three-dimensional characteristics yields a 3D-FEM modeling, is described. In section III, the 3D numerical model that takes into account coupling with external electrical circuit is presented. In section IV, numerical model is validated using experimental results for different cases: without short-circuit; with a short-circuit fault at low speed. Finally, the numerical model is used for determination of short-circuit currents and magnetic flux density in magnets at higher speeds.

II. Presentation of the Machine

The AFPM generator is composed of a stator and two externals six-pole rotors with rare-earth permanent magnets (Fig. 1). Since the magnetic flux paths are in all three directions of the magnetic circuit, a Soft Magnetic Material (SMC) with isotropic magnetic properties has been used for the stator core. The seven phases are obtained with toroidal coils distributed into 42 slots. The two rotors are identical but with an angular shift of 360/84 degrees between them in order to reduce the cogging torque. The spatial magnet repartition implies non-sinusoidal electromotive forces as it is usual for multiphase machines. All these specificities imply that analysis by FEM is necessary. Rated torque value of 65Nm torque is obtained for a 5.1A RMS current, rated power of 5.1kW rated power, for a 750RPM speed. More precise data are given in [6].

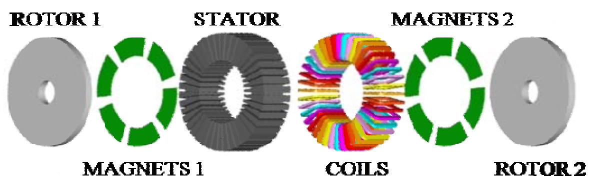

Fig. 1. Studied machine

For the numerical model, the small shift between the rotors imposes the mesh (791506 tetrahedron elements and 141937 nodes) of one sixth of the machine represented in Fig. 2.

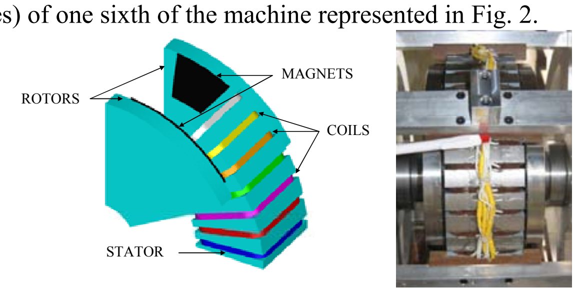

Fig. 2. One sixth of the seven-phase studied machine (left), whole machine (right)

III. Numerical Model

A. *Magnetostatic problem*

Let us consider a domain D of boundary Γ. In the case of magnetostatic problem, the distribution of the magnetic field **H** and the magnetic field density **B** is given from the Maxwell's equations such as:

$$\operatorname{div} \mathbf{B} = 0 \quad \text{with } \mathbf{B}.\mathbf{n} = 0 \text{ on } \Gamma_B \tag{1}$$

$$\mathbf{curlH} = \sum_{k=1}^{7} \mathbf{N}_k i_k \quad \text{with } \mathbf{H}\times\mathbf{n} = 0 \text{ on } \Gamma_H \tag{2}$$

with:

- $\mathbf{N}_k$ the turn density field,

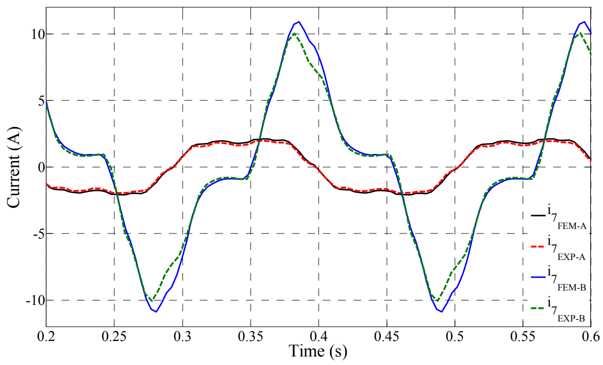

Fig. 7. Comparison between numerical and experimental results for the seventh current at 10rad/s

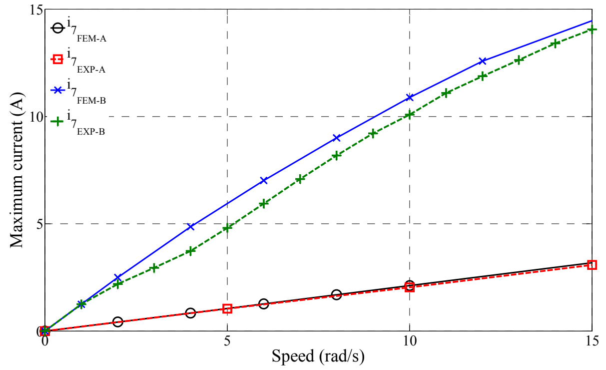

Fig. 8. Maximum current in the seventh winding for different speeds

B. *Study of flux magnetic density inside a permanent magnet*

By using a numerical model, it is possible to determine the drop of the magnetic flux density inside the magnet due to the demagnetizing short-circuit currents. In Fig. 9, the magnetic flux density at the center of a permanent magnet, with and without short-circuit fault, is given at 30rad/s. In both cases, the effect of the slots (7 slots for 60°) on the variations of the flux density is obvious. In case B, it appears also the demagnetizing effect of the short-circuit current in two adjacent phases. The two coupled phenomena imply a complex waveform for the magnetic flux density. Nevertheless, it is easy with the obtained results to check that the minimum value that yields irreversible demagnetization is not reached.

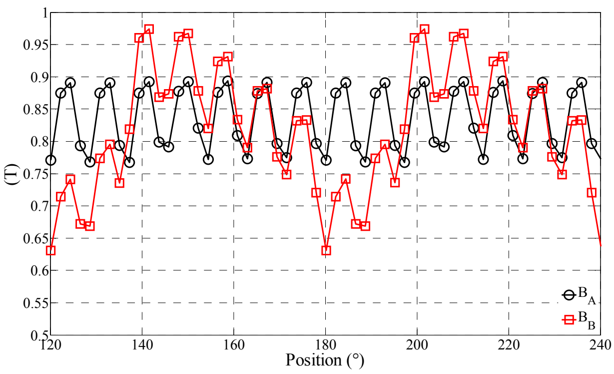

Fig. 9. Magnetic flux density inside a permanent magnet

Fig. 10 presents the variation of the lowest value of the magnetic flux density inside a permanent magnet versus the rotation speed for both studies. In the case of the study B, the magnitude of the short circuit current on the sixth and seventh winding is more important compared to the others windings.

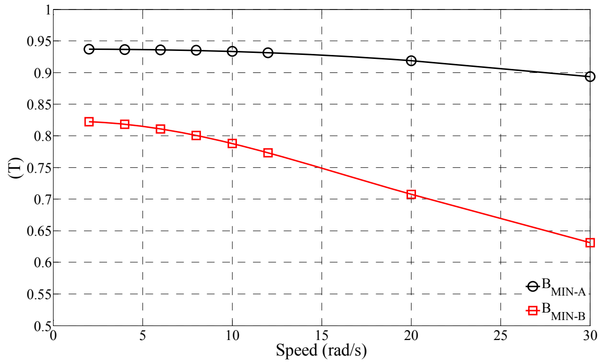

Fig. 10. Lowest value of the magnetic flux density inside a permanent magnet

V. Conclusion

The effect of short-circuit currents for an AFPM with two shifted rotors and open slots has been calculated with a 3D-FEM. Comparison of calculated currents with experimental ones in case of short-circuit at low speed has validated the model that has been then used to predetermine the complex magnetic flux density in the center of a magnet. It is thus possible to check that irreversible demagnetization is not reached before the action of the overload protection devices. The numerical model can be still improved by modeling the SMC with non-linear characteristics that becomes necessary at high speeds with high short-circuit currents.

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