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.


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].

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. 1. Studied machine](image1)

![Fig. 2. One sixth of the seven-phase studied machine (left), whole machine (right)](image2)

III. NUMERICAL MODEL

A. Magnetostatic problem

Let us consider a domain D of boundary \( \Gamma \). In the case of magnetostatic problem, the distribution of the magnetic field \( \mathbf{H} \) and the magnetic field density \( \mathbf{B} \) is given from the Maxwell’s equations such as:

\[
\text{div} \, \mathbf{B} = 0 \quad \text{with} \quad \mathbf{B} \cdot \mathbf{n} = 0 \text{ on } \Gamma_B
\]  \( (1) \)

\[
\text{curl} \mathbf{H} = \sum_{k=1}^{N} N_k \mathbf{i}_k \quad \text{with} \quad \mathbf{H} \times \mathbf{n} = 0 \text{ on } \Gamma_H
\]  \( (2) \)

with:
- \( N_k \) the turn density field,
In order to take into account the magnetic behaviour of materials, the relationship between $B$ and $H$ is introduced. In the case of permanent magnets, this one can be supposed linear such as:

$$B = \mu_0 H + B_r$$

with $B_r$ the remanent magnetic flux density of the permanent magnet and $\mu_0$ its magnetic permeability. For the SMC material, a linear model appears to be sufficient \[6\] in case of permanent magnet machines with large air gap:

$$B = \mu H = \mu_0 \mu_r H$$

with $\mu_0$ the magnetic permeability of the vacuum and $\mu_r$ the relative permeability. To solve the problem composed of the previous relations, potential formulations can be used. However, the scalar potential formulation has been chosen in the paper in order to limit the number of unknowns.

### B. Scalar potential formulation

In a scalar potential formulation, a magnetic scalar potential $\Omega$ is introduced. For each winding “$k$”, a magnetic field $K_k$ is determined. The fields $K$ are defined in the whole domain such as:

$$\text{curl } K_k = N_k \text{ with } K_k \times n = 0 \text{ on } \Gamma_H \text{ for } k = [1,7]$$

Then, by using (2), the magnetic field $H$ is expressed as function of $\Omega$ and $K$.

$$H = \sum_{k=1}^{7} K_k i_k - \text{grad } \Omega \text{ with } \Omega = \text{cst on } \Gamma_H$$

In the case of numerical solution such as the finite element method (FEM), elements of Whitney can be used for discretization of the potential $\Omega$ and the fields $K$ and $N$. Then, $\Omega$ is discretized in the nodal element space and the fields $K$ and $N$ in the edge and facet element spaces respectively \[8\]. To determine $K_k$ and $N_k$, a tree technique has been carried out \[9\]. By using (1), a weak formulation to solve is deduced such as:

$$\int_{\Omega} B \text{grad } \Omega \text{ dD} + \int_{\Omega} B_i \text{grad } \Omega \text{ dD} = 0$$

This relation supposes a volume integral in $\Omega$ and the field $K_k$ associated with the winding “$k$”.

To simulate movement, different techniques exist. The choice for the simulation is a step locked approach based on slip surfaces with regular meshes defined in the middle of each air gap. Thus, the displacement is modelled by a circular permutation of the unknowns, according to the mesh step or an integer multiple of this last one \[10\]. The rotation speed $\Omega_s$ (rad/s) is given by the following relation:

$$\Omega_s = \frac{\Delta \theta}{\Delta t}$$

with $\Delta \theta$ the angular step in the slip surfaces and $\Delta t$ the time step. The electromotive force $e_k$ associated with the winding “$k$” can be simply deduced by the computation of the magnetic flux $\Phi_k$ at each time step. Figure 3 presents the distribution of the magnetic flux density due to the permanent magnets in the studied machine.

![Fig. 3. Distribution of the magnetic flux density due to the permanent magnets](image)

### C. Coupling with external electric circuit

The windings of the AFPM generator are connected to an electric load. The resistor of each winding is denoted $r_p$. Fig. 4 presents the coupling between the FEM model and the loads which are modeled by resistors $R_c$.

![Fig. 4. Coupling between FEM model and the electric loads](image)
In order to take into account the coupling between the external electric circuit and the windings, new relations must be added to (7). The current flowing through each winding becomes a new unknown in the problem. By using Fig. 4, the current of the seventh winding can be arbitrary written as function of all other currents by:

\[ i_7 = \sum_{k=1}^{6} i_k \]  

(10)

The circuit is composed of six electric loops. Six new relations must be then introduced such as:

\[ (r + R) i_k - (r + R) i_i + c_i - e_i = 0 \text{ with } k=[1,6] \]  

(11)

with the electromotive forces calculated by the following relation:

\[ e_i = \frac{d\Phi_i}{dt} \text{ with } i=[1,7] \]  

(12)

Finally, the equation system to solve is composed of (6), (7) and (11).

D. Numerical model taking into account a short-circuit fault

In the case of a short-circuit current between several windings of the machine, the electrical equations of the previous section must be modified. To illustrate the used approach, we consider an electrical fault such as this one presented in Fig. 5.

Five windings are connected to resistors \( R_c \) and a short circuit is introduced between two other windings. In this condition, we can express the currents \( i_5 \) and \( i_7 \) such as:

\[ i_5 = - \sum_{k=1}^{4} i_k \] \text{ and } \[ i_7 = -i_6 \]  

(13)

Five relations can be written to characterize the electric circuit of Fig. 4 such as:

\[ (r + R) i_k - (r + R) i_i + c_i - e_i = 0 \text{ with } k=[1,4] \]  

(14)

\[ r_i i_k - r_i i_i + c_i - e_i = 0 \]  

(15)

The system to be solved is thus composed of (6), (7), (13), (14) and (15).

IV. VALIDATION OF THE NUMERICAL MODEL AND DETERMINATION OF THE FLUX MAGNETIC DENSITY

Firstly the numerical model is validated by comparison of the calculated short-circuit currents with experimental measurements at low speeds (0 to 15rad/s). Secondly the numerical model is used to evaluate the effect of the demagnetizing armature reaction during the short-circuit fault: the minimum value of the magnetic flux density that occurs inside the magnet is calculated.

For two studies (with and without an electrical fault), the variation of currents and magnetic flux density in magnet versus the rotation speed are considered. We denote respectively by A and B the study without and with fault and by FEM and EXP the results obtained by the numerical model and the experimental measurements.

A. Validation of the numerical model

Fig. 6 presents waveforms of the calculated currents in the case of the study B for a speed of 30rad/s. We can clearly observe different waveforms and peak current amplitudes. In accordance with Fig. 5, \( i_6 \) and \( i_7 \) currents are opposite and have the maximum peak value.

Fig. 7 compares only the peak values but from 0 to 15rad/s: maximum relative error of 23% is observed. As consequence, considering incertitude on the magnetic material, it can be admitted that the linear numerical model is experimentally validated from 0rad/s to 15rad/s.
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 30 rad/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. 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.

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.

REFERENCES


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