Analysis of local forces distribution in high speed permanent magnet motor

Abstract. In the paper Author focuses on the analysis of the electromagnetic force distribution in a high speed permanent magnet motor (HSPM). The method of local forces calculation in a 2D finite element model of the machine has been proposed and discussed. The numerical model has been elaborated in the Maxwell environment. Two operation modes of the machine have been considered: (a) no-load (only magnets generate force) and (b) rated load for steady state. The local force distribution, forces acting on stator tooth and on each side of permanent magnet have been computed.

Streszczenie. W artykule autor przeanalizował rozkład sił pochodzenia elektromagnetycznego w wysokoobrotowym silniku magnetoelektrycznym. Zaprezentowano metody obliczania sił lokalnych dla dwumywnianego modelu MES rozważanej maszyny. Model numeryczny został opracowany w środowisku Maxwell. Rozważono dwa tryby pracy maszyny: (a) bez obciążenia (pole magnetyczne generowane jest tylko przez magnesy), oraz (b) przy obciążeniu znamionowym w stanie ustalonym. Obliczono rozkład sił lokalnych, siły działające na ząb stojana oraz na wewnętrznej i zewnętrznej stronie magnesu. Analiza rozkładu sił lokalnych w wysokoobrotowym silniku o magnesach trwałych.

Keywords: local forces, permanent magnet motor.
Słowa kluczowe: siły lokalne, silnik magnetoelektryczny.

Introduction

One of the most difficult to eliminate sources of vibration in electrical machines are stresses derived from electromagnetic field. In the literature, the problem of determining the electromechanical stress the most common boils down to determining the distribution of local forces. For calculating local magnetic forces (distribution of force) the several different methods can be used. These techniques derive from methods of the total magnetic force computation e.g., methods based on the virtual work principle, Maxwell stress tensor, equivalent magnetization models [1,2].

Recently to calculate the electromagnetic force distribution the finite element (FE) method is widely used. Accessible of professional electromagnetic FEM software e.g. Maxwell, Infolytica, Comsol are employed. Author of this article decided to perform analysis using the Maxwell software, which is a part of Ansys system that allows for the multi-domain coupled problem studies.

In this paper force distributions on stator and permanent magnets surface in a high speed electrical machine with surface mounted permanent magnets are presented. The rated power of the investigated motor is about 0.75 kW with rated speed equal to 18000 rpm. Such machines are widely used for home appliances’ purposes.

Electromagnetic force calculation

The relationships that describe the electromagnetic forces are formed on the basis of the virtual work principle. Force obtained from virtual work method can be expressed as:

\[ F = \frac{dW}{ds} \frac{\partial}{\partial s} \left[ \int_{V} B \cdot \nabla \times H \right] dV \]

where: \( B \) – flux density, \( H \) – field strength, \( V \) – volume, \( s \) – virtual displacement.

In the virtual work principle one can apply the two representations of virtual displacement, namely: (a) the virtual displacement of field sources in relation to the fixed space with magnetic field, (b) the virtual displacement of the region where the force acts, e.g. rotor region in relation to the fixed outer region, e.g. stator region. As a result we obtain the 2 categories of formulas. First category (a) are the force density formulas, e. g. equivalent magnetization current method where force density is described similar to Lorenz force:

\[ f = J_m \times B \]

where magnetization current density is considered instead of the magnetic material:

\[ J_m = \nabla \times M \]

where: \( M \) – the magnetisation vector.

Next example is the equivalent magnetic charge source method where the following formula is used:

\[ f = \rho_m H \]

Here, the magnetic materials are replaced by the equivalent distribution of magnetic charges the charge density defined as:

\[ \rho_m = -\mu_0 \nabla \times M \]

where: \( \mu_0 \) – the magnetic permeability.

In equations (2), (4) one assumes that the conduction current density is equal to zero. The second category of formulas (b) are the stress tensor formulas, e.g. the Maxwell stress tensor formula [3], where the force density is calculated as:

\[ f \approx \frac{1}{\mu_0} (B n) B - \frac{1}{2\mu_0} B^2 n \]

where: \( n \) – normal outward unit vector.

The Korteweg-Helmholtz force density method also belong to the stress tensor formula category. The force density in this method is expressed as [4]:

\[ f = \sum_{i} \frac{\partial W}{\partial \alpha_i} \nabla \alpha_i - \nabla \left( \sum_{i} \alpha_i \frac{\partial W}{\partial \alpha_i} \right) \]

where: \( W \) – magnetic-field energy density, \( \alpha \) – represents material properties.

For exact solution of the Maxwell equations each of these methods leads to the same results of global force calculation, therefore they are considered to be equivalent. In practice it is important to note that methods giving the same proper value of global force do not guarantee the identity of the results in the case of local force and force density calculations. This is because the global force represents the sum (integral) that consists of components describing the local forces and the given value of sum can be obtained by summation of components of different values.

The additional complications occur when the finite element (FE) method is applied. Even for global force calculation the commonly used FE packages give the satisfactory accuracy only for relatively dense of FE meshes.
Therefore, in the paper a special attention is paid to the accuracy of local force calculation using FE method. In the investigation the results presented in [1] have been taken into account. The authors of paper [1] considered several methods of local force calculation. They didn't investigate the local forces themselves, but rather the deformation of ferromagnetic material due to forces. Obtained results have shown that only the magnetisation current method gave incorrect deformations.

Local force distribution in HSPM motor

A structure of the considered HSPM motor is shown in fig. 1. Torque and electromotive force characteristics of studied motor were presented in [5].

As it was mentioned the calculations have been performed in the Maxwell environment. In relation to the methodology of force calculation the software specification is limited to the information that force is calculated using the virtual work method. For 2D analysis is possible to determine the two types of force fields: edge force density (EFD) and surface force density (SFD). In earlier work [6] the author has shown that SFD gives inaccurate results in case of 2D studies, and so, force distributions presented in the article are related to values of EFD.

\[
F_{\text{tooth}} = \sum_i \text{efd}_i \cdot l_i
\]

where: \(\text{efd}_i\) – edge force density for edge of finite element, \(l_i\) – length of edge of finite element. Index \(i\) is equal to number of finite elements edges which are part of the stator tooth.

The calculations were repeated for different rotor positions. The rotor was rotated in counterclockwise direction. Obtained characteristics of normal (to outer surface) component of force acting on stator tooth for no- and rated load state are presented in fig. 4. The negative values of these forces mean that the sense of force is from stator to rotor. The difference between maximum values of normal component of \(F_{\text{tooth}}\) is about 10 N which is about 21.5 % of the maximum value of force at rated load operation. This shows out that force acting on stator teeth is produced mainly by the permanent magnets.
Fig. 3. Local force distributions on stator surface at no-load (a) and rated load (b) operation mode

Fig. 4. Normal component of force acting on stator tooth as a function of rotor angle

Fig. 5. Transversal component of force acting on stator tooth as a function of rotor angle

Table 1 Forces acting on permanent magnet

<table>
<thead>
<tr>
<th>component</th>
<th>global force</th>
<th>centrifugal force</th>
<th>inner surface force</th>
<th>outer surface force</th>
</tr>
</thead>
<tbody>
<tr>
<td>normal</td>
<td>-33.73 N</td>
<td>781.24 N</td>
<td>-126.69 N</td>
<td>100.8 N</td>
</tr>
<tr>
<td>transversal</td>
<td>-0.27 N</td>
<td>--</td>
<td>0.1 N</td>
<td>-0.68 N</td>
</tr>
</tbody>
</table>

Conclusion

The difficulties in determining correct local electromagnetic force distribution have been discussed. The presented model of the HSPM Motor has been carefully suited for determining local forces distribution. Obtained result can be successfully used as a source for calculation of mechanical stress in machine. The high pulsations of force characteristic presented in fig. 4 (especially for rated load state) may indicate that noise excited by the magnets will be included in a wide range of frequency spectrum. Presented analysis shows that radial forces acting on stator teeth are produced mainly by permanent magnets.

It should be noticed that one of the disadvantages of the used software is the need to create the additional air-gap around permanent magnet (or another part of machine being in contact with another one) in order to evaluate EFD. The interesting finding based on the obtained result is that forces acting on the inner and the outer surface of permanent magnet are on similar level.

This paper was supported by research grant 04/42/DSPB/0161.

REFERENCES


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