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Analysis of local forces distribution in high speed permanent magnet motor

***Abstract**. In the paper Author focus 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 dwuwymiarowego 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 wewnętrzną i zewnętrzną stronę 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:

$$\boldsymbol{F} = \frac{dW(s)}{ds} = \frac{\partial}{\partial s}\left[\int_V \left(\int_0^H \boldsymbol{B}\, d\boldsymbol{H}\right) dV\right] \tag{1}$$

where: $\boldsymbol{B}$ – flux density, $\boldsymbol{H}$ – 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:

$$\boldsymbol{f} = \boldsymbol{J}_m \times \boldsymbol{B} \tag{2}$$

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

$$\boldsymbol{J}_m = \nabla \times \boldsymbol{M} \tag{3}$$

where: $\boldsymbol{M}$ – the magnetisation vector.

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

$$\boldsymbol{f} = \rho_m \boldsymbol{H} \tag{4}$$

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

$$\rho_m = -\mu_0 \nabla \boldsymbol{M} \tag{5}$$

where: μ_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:

$$\boldsymbol{f} = \frac{1}{\mu_0}(\boldsymbol{B}\boldsymbol{n})\boldsymbol{B} - \frac{1}{2\mu_0}B^2\boldsymbol{n} \tag{6}$$

where: $\boldsymbol{n}$ – 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]:

$$\boldsymbol{f}_e = \sum_i \frac{\partial W}{\partial \alpha_i}\nabla \alpha_i - \nabla\left(\sum_i \alpha_i \frac{\partial W}{\partial \alpha_i}\right) \tag{7}$$

where: W – magnetic-field energy density, α – 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.

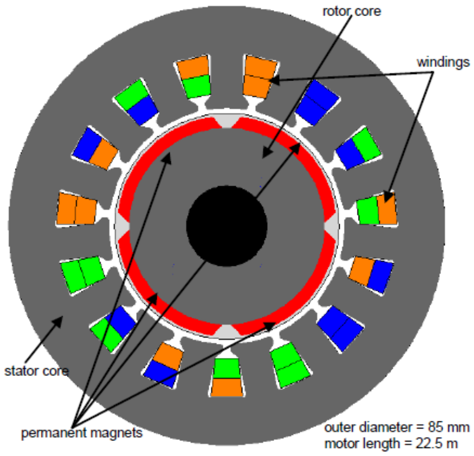

Fig. 1. Structure of analysed HSPM motor

In fig. 2a and 3a the force distributions on stator surface at no-load operation mode (force is generated only by permanent magnets – the current in the winding equals zero) is shown. The local forces are concentrated on the inner surface of stator teeth. On the other surfaces the local forces are much lower. The distribution at the rated load operation mode is presented in fig. 2b and 3b. In this case the motor is supplied in the BLDC mode, this means that current flows only through two phases while remaining phase is left open. At the rated load mode the value of forces are higher and force vectors slightly rotate in relation to the no-load state.

Using the obtained force distribution, the force acting on stator tooth was calculated as:

$$F_{tooth} = \sum_i efd_i \cdot l_i \qquad (8)$$

where: efd – *edge force density* for edge of finite element, l – 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_{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.

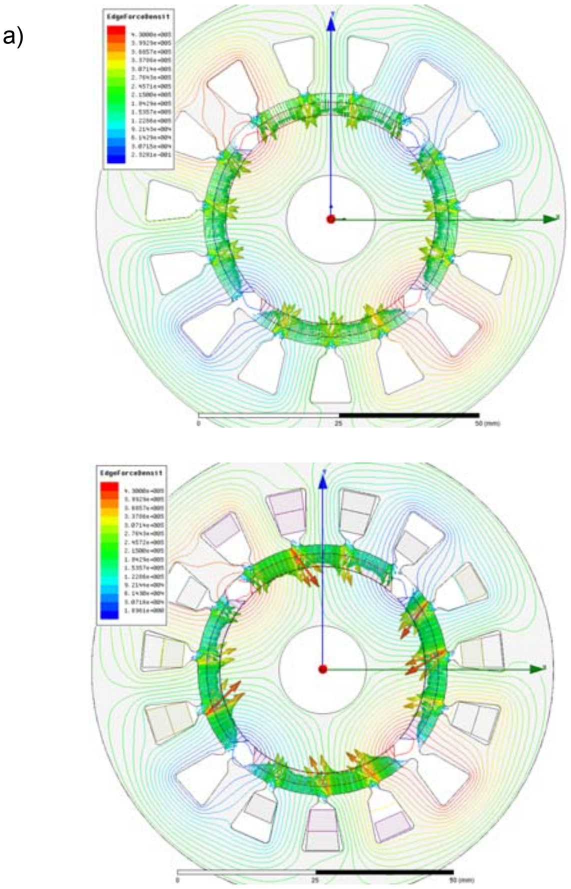

Fig. 2. Local force distributions on stator surface at no-load (a) and rated load (b) operation mode

In fig. 5 the characteristics of transversal component of force acting on stator tooth are presented. The negative values are related to the clockwise direction. Maximum values of the transversal components of force F_{tooth} are over ten times smaller than the maximum values of normal components of this force, at both operation states. For the no-load state the mean value of F_{tooth} from fig. 5 is equal to zero. However for the rated load the mean value is not zero, and it represents the reaction force on the global force that generates the torque.

In order to calculate EFD for permanent magnets it is necessary to create an air-gap between the rotor core and permanent magnets. This air-gap can represent e.g. an adhesive layer which exist in real machine. However this procedure significantly increases the number of mesh elements. In the presented model the additional air-gap is 0.1 mm thick. The force distribution on the permanent magnet surface is shown in fig. 6. The global force acting on permanent magnet presented in fig. 6 is equal to -33.73 N. When the motor runs with rated speed the centrifugal force acting on the magnet is equal to 781.24 N. Therefore, it is necessary to add a special sleeve on outer magnets surface, which is neglected here.

Utilizing equation (8), force acting on the inner and on the outer surface of permanent magnet was calculated. Summations were performed on the inner and on the outer edge of the magnet, respectively. Obtained results are summarized in Table 1.

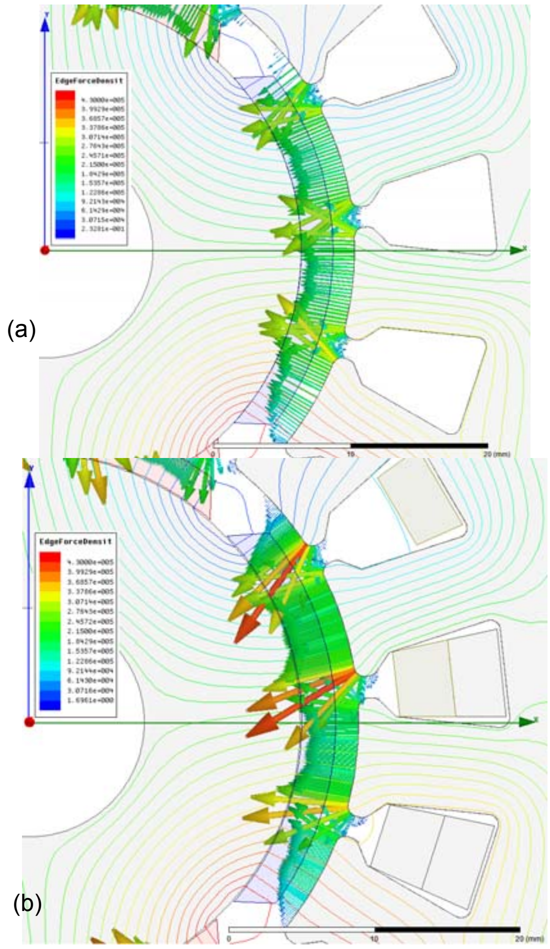

Fig. 3. Local force distributions on stator surface at no-load (a) and rated load (b) operation mode

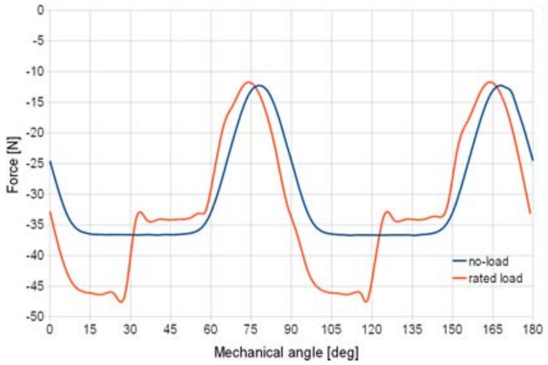

Fig. 4. Normal component of force acting on stator tooth as a function of rotor angle

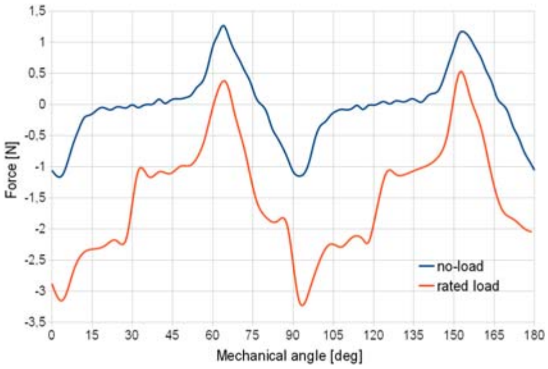

Fig. 5. Transversal component of force acting on stator tooth as a function of rotor angle

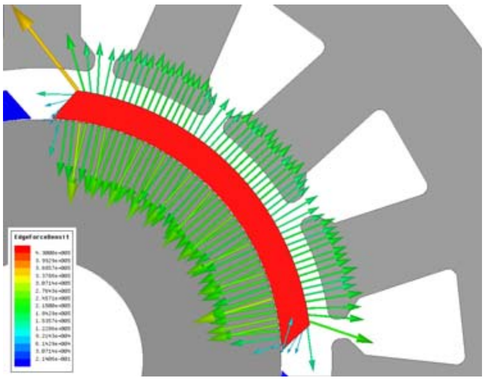

Fig. 6. Local forces distribution on permanent magnet surface at no-load operation mode

Table 1 Forces acting on permanent magnet

component	global force	centrifugal force	inner surface force	outer surface force
normal	-33.73 N	781.24 N	-126.69 N	100.8 N
transversal	-0.27 N	--	0.1 N	-0.68 N

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.

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