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LINEAR PARALLELEPIPEDIC ELECTRIC MACHINE: LOSSES IN THE MOVING PLATE

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ABSTRACT

This paper details the calculation of losses in the flat moving plate (rotor) consisting of permanent magnets (NdFeB) between two fixed stators of a linear parallelepipedic electric machine. The resistivity of Neodymium-iron-boron (NdFeB) magnets is between 120 and $160*10^{-8}$ Ω.m. The heat dissipation from the two stationary stators can cause a temperature rise that demagnetizes the highly temperature-sensitive NdFeB magnets. The heating of the NdFeB magnets reduces the remanent induction Br and therefore the tangential force. In addition, this heating can damage adhesives, resins or varnishes, which can cause permanent magnets to loosen. Eddy current losses in permanent magnets are created by the space and time harmonics of the armature reaction field, as well as by the permeance variations seen by the magnets (alternating teeth and slots); they cannot be neglected. The losses in the magnets (moving plate) of the linear parallelepipedic machine are determined by the finite element method using the ANSYS MAXWELL software.

KEYWORDS: Linear parallelepipedic machine - Moving plate - Losses in permanent magnets – Finite Element Method.

1. INTRODUCTION

Linear machines with permanent magnets have become an almost unavoidable choice in the industrial field, due to their high performance in terms of torque and power density.[1] Nevertheless, permanent magnets, especially those based on rare earths NeFeB or Sm-Co, remain temperature-sensitive, which can cause them to demagnetize. The heating of permanent magnets is due to local eddy current losses caused by the spatio-temporal variation of induction. Thus, the estimation of losses in permanent magnets is an important area of research in the field of electrical machine modelling for two main reasons: to maximise machine performance such as efficiency and torque/power, and to predict the thermal behaviour of machines for critical operating points, in particular the heating of permanent magnets.

Different modelling and estimation work on these losses can be found in the literature. In.[2,3,4] the authors propose a 2D analytical model based on analytical resolution by considering the reaction of the armature magnetic field on permanent magnets or limited-resistance magnets for synchronous machines with surface-mounted magnets. In,[5] the authors propose a model based on the solution of the diffusion equation, using the sub-domain method, for synchronous machines with inserted magnets. Other simplified models have been developed.[6-7] They are based on the calculation of the flux created by the variation of induction in permanent magnets, by decomposing permanent magnets into concentric turns and assuming that eddy currents develop in these turns.

Hard materials have a high uni-axial magneto-crystalline anisotropy and the walls of the domain have more difficulty to move compared to soft materials. The Bertotti loss separation formalism used in soft materials is not relevant in a magnetic material with permanent magnets. In flat linear machines with permanent magnets, the losses in the magnets are mainly due to the induced currents created by the variation of induction in the solid material.

There are three causes for these induction variations

- The harmonics produced by the stator winding

Dental winding machines are characterized by a magnetomotive force (MMF) with a large harmonic content, which do not rotate at the same speed as the moving plate and induce eddy currents.

- Permeance harmonics

As the moving plate moves, the magnetic induction inside the magnets changes due to the variation in permeance created by alternating teeth and slots, leading to the formation of eddy currents inside the magnets.

- Temporal harmonics

Power electronics converters produce temporal harmonics on the supply currents that generate field components that do not rotate at the same speed as the moving plate.

As regards the winding of electrical machines, the choice of a bar winding is justified by the advantages it offers over a distributed winding. Indeed, the heads of the coils are reduced, which reduces Joule losses and allows high efficiency. Tooth torque amplitude and torque ripples are also reduced.[8-9] In addition, it is easier to design and assemble. However, the magnetomotive force is rich in space harmonics, which can lead to high eddy current losses in permanent magnets.[10-11]

In this paper, the machine being used will be described first. Then, the model for calculating eddy current losses in permanent magnets will be presented. This model takes into account the 3D distribution of eddy currents in permanent magnets.

2. Linear Electric Machine Description

Linear machines have been and continue to be designed considering a large variety of topologies. They are classified according to the morphology and the AC-type. Linear machines are flat or tubular. They either have a long stator, with the mover shorter than the stator or a short stator, with the mover longer than the stator. The stator slots are of single layer type or double layer one. Beyond energy efficiency, linear machine concepts exhibit: high velocity , high acceleration, high accuracy of the position sensing and high lifetime with less maintenance.[12-13]

The fixed parts (stators) of the linear electric machine are made up of a magnetic circuit in M300-35A rectangular form, in laminated sheets equipped with the slots intended for three-phase winding aluminum bars. The magnetic circuit is laminated in stacked plates cut to their thickness (of 0.5 mm). The number of stacked plates is proportional to the width of the magnetic circuit. The plate is punch-cut in a single operation from a strip of sheet metal, first insulated on both sides by a phenolic class H varnish. The plate hole profile has a circle shaped that will help stack plates for the appropriate height of the magnetic circuit to be dipped in the oven. The side of the plate bore has 36 slots intended to receive the winding bars after stacking.[14]

The coil is three-phase-series bar star. Each bar is composed of a rectangular aluminum section (7mmx2mm) to ensure transverse field compensation of Roëbel slot process. Bar winding has several advantages over traditional winding: good slot filling factor (greater than 95%); minimization of solid insulation and the potential difference between bars; better performance; and good thermal behavior in the slot.The difficulty in carrying out winding with more than one layer including the additional losses are disadvantages because it is a low-voltage winding.

The linear electric machine is protected by an aluminium cover called enclosure against ingress of moisture, dust, atmospheric impurities and any foreign materials.The PM mover consists of a PMs made up of NdFeB (54mm*5mm*3mm alternating North-South), magnetized in the transversal direction. The magnets are glued to a brass frame. The friction sheet is made of bronze 0.1 mm thick to ensure strength and mechanical rigidity. Anaerobic glue (polymerized in the absence of air) of acrylic type is used. The linear electric machine is a parallelepipedic structure with two air gaps (Figure 1).

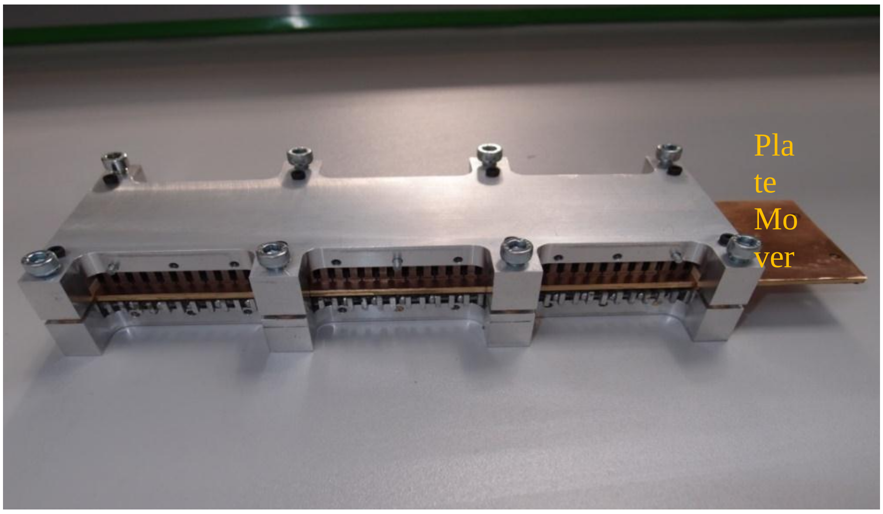

Figure 1: Linear Electric Machine.

3. Analytical models for calculating losses in the moving plate

The superposition principle is used to estimate losses in permanent magnets. The losses due to slot effects and space-time harmonics of the magnetomotive force (MMF) of the stator winding are calculated separately and the sum of all these contributions gives the value of the losses. This principle is valid when the saturation of the laminations and the skin effect are negligible.

3.1. Losses due to tooth harmonics

Several models have been developed in the literature for the calculation of losses due to space-time harmonics of the magnetomotive force (MMF) of the stator winding. Some models.[15] are based on the calculation of the flux created by the variation of induction in permanent magnets assuming that the eddy currents develop in the concentric turns.

These models have been extended to take into account the variation in the trajectory of the induced currents as a function of the wavelength of the space harmonics. Their drawbacks concern the induction which is considered constant over the entire thickness of the magnet. Analytical models based on the analytical resolution of Maxwell's equations have improved the accuracy of the evaluation of losses in magnets. Some of these models are expressed in the Cartesian coordinate system.[16] and the machine modelled by superimposing layers as in Figure 1 for joined magnets. The currents induced in the magnets have an axis of symmetry and close on a polar pitch.

Table 1: 2D Cartesian model of the linear parallelepipedic machine with permanent magnet.

STATOR with permeability μ_1
AIR GAP with permeability μ_2
PERMANENT MAGNET (PM) with permeability μ_3
AIR GAP with permeability μ_2
STATOR with permeability μ_1

A model based on the solution of the Maxwell equations in 2D was presented [17]. The authors determine the vector potential A in the region of the magnets assuming zero conductivity in a first step. They then calculate the induced current density J in the magnet given by equation (1).

$$J = -\sigma \frac{\partial A}{\partial t} - J^0, \quad (1)$$

The eddy current losses in the magnet are calculated by integrating the eddy current density induced on the volume of the plate (permanent magnet).

$$P_{PM} = \int_V \frac{J^2}{\sigma} dV, \qquad (2)$$

J^0: Mean value of the current density in the magnet at time t

σ: Electrical conductivity of the magnet

The losses calculated by this model are very close to those obtained by finite elements in magnetodynamic regime as long as the skin effect is neglected.

3.2. Losses due to dental effect

The opening of the slots leads to large field variations and thus to significant losses in the magnets. Figure 2 illustrates the effects of slot openings on the induction level in magnets.

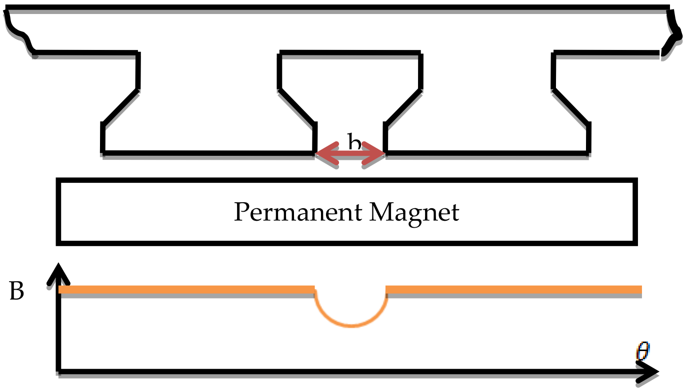

Figure 2: Effect of slot openings on induction.

The simplified analytical model for the calculation of stator gearing losses is given in.[18,19] The analytical equation shows that the losses are proportional to the peak value of the induction B, the square of the moving plate speed V, the number of slots N and the volume of the magnet Va.

$$P = \frac{1}{2} N \cdot \sigma \cdot V_a B^2 V^2, \qquad (3)$$

For a more precise evaluation of losses in magnets, an analytical model showing the harmonics of teeth has been proposed in.[20] In this model the losses are determined in two steps. In the first step, the change in induction in the magnets due to slot effects is determined, then the induced currents and finally the losses are calculated. To calculate the distribution of the induction in the air gap, the induction is assumed to be equal to the product of the induction in the magnets in the case of a smooth stator by a modulation function which takes into account the effect of slots on the field distribution. This modulation function is determined analytically using conformal transformers as shown in reference.[21]

The overall value of losses in permanent magnets is the sum of losses due to slot effects and space-time harmonics of the magnetomotive force of the stator winding.

The moving plate consisting of permanent magnets is subjected to a flux density B, parallel to the moving plate in the Ox direction. Small amplitude induced currents will not significantly affect the flux density B shown in Figure 3.

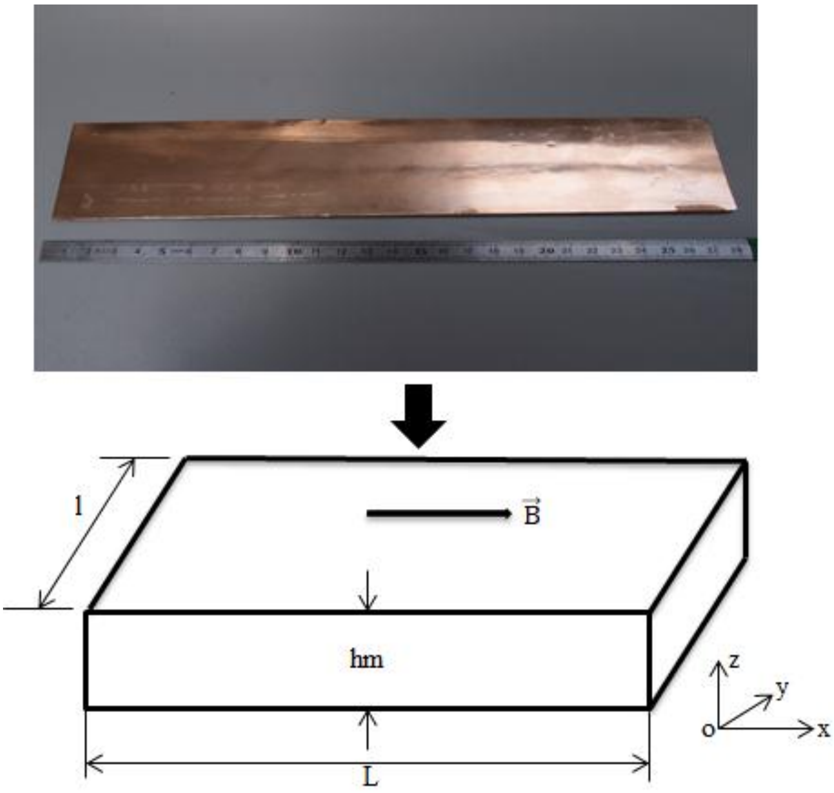

Figure 3: Losses in the moving plate.

Under these conditions, it can be assumed that the induced current density J does not depend on x or y. The expressions for J and E are given by (4) and (5) respectively.

$$J = \sigma E, \tag{4}$$

$$E_y(z) = \frac{\partial B_x}{\partial t} z, \tag{5}$$

The power dissipated in the moving plate is given by (6).

$$P_{PM} = \int_V \sigma E_y^2 \, dV = \frac{\sigma h_m^2}{12}\left(\frac{\partial B_x}{\partial t}\right)^2 V.N \quad (W), \tag{6}$$

V=L.l.hm (volume of a permanent magnet), the total volume = V.N; N: number of magnets. By introducing the power density, and the average time equation (6) becomes (7).

$$P_{PM} = \frac{\sigma h_m^2}{12} \frac{1}{T} \left(\frac{\partial B_x}{\partial t}\right)^2 dt \quad (W/m^3), \tag{7}$$

T: period of induction B.

If the component of induction B in the Ox direction is sinusoidal, expression (7) becomes (8).

$$P_{PM} = \frac{\sigma h_m^2}{24} \omega^2 B_m^2 \quad (W/m^3), \tag{8}$$

Losses in permanent magnets are quadratically dependent on its thickness.

4. Calculation of losses by the Finite Element Method

The analytical model for the calculation of losses in magnets is based on a number of assumptions: negligible magnetic reaction field of magnets; inaccuracy in the calculation of induced currents in magnets.

The complete process of simulation process consists of three parts: preprocessing process, solver process and post-processing process. During preprocessing process environmental conditions for simulation are prepared: geometrical data, material properties, excitation source and boundary conditions using data in table 2 and 3 for the geometrical machine data and NdFeB properties.

Table 2: Machine dimensional parameters.

Element	**Symbol**	**Value (mm)**
Slot opening height	-	1.0
Slot wedge height	-	0.0
Slot body height	-	5.0
Slot opening width	-	0.5
Slot wedge width	-	2.5
Slot body bottom width	-	2.5
Slot pitch	-	5.0
Pole pitch	τ_p	5.0
PM length	-	5.0
PM thickness	hm	3.0
Air gap	g	0.3
Generator length	-	230.0
Generator width	-	50.0
Stroke	Ls	20.0

Table 3: Permanent magnet (NdFeB) properties.

Permanent Magnet	**Thermal conductivity λ(W/mK)**	**Heat capacity C(kJ/kgK)**
NdFeB	8-9	0.45

The software considered for the calculation of losses in magnets is the ANSYS MAXWELL software. It enables the carrying out of transient simulations.

Meshing process is one of the important steps to get better accuracy from the computation, but it also result in longer time consumption for the computation process if we chose to use small size elements for the whole model. To deal with accuracy and computation time, a particular area which is more sensitive toward the change of variable is chosen. In our model, air gap is the area that should have a better accuracy.

Figure 4, illustrates the losses in permanent magnets by the finite element method, using the ANSYS Maxwell software. The losses in average permanent magnets are of the order of 2.3 W. The velocity is equal to $2\tau_p f$, where τ_p is the polar pitch and f is the frequency. The plate moves at a speed of 0.5 m/sec and the polar pitch being 5 mm, a frequency of 50 Hz is obtained. Figure 5 shows a simulation obtained by ANSYS.

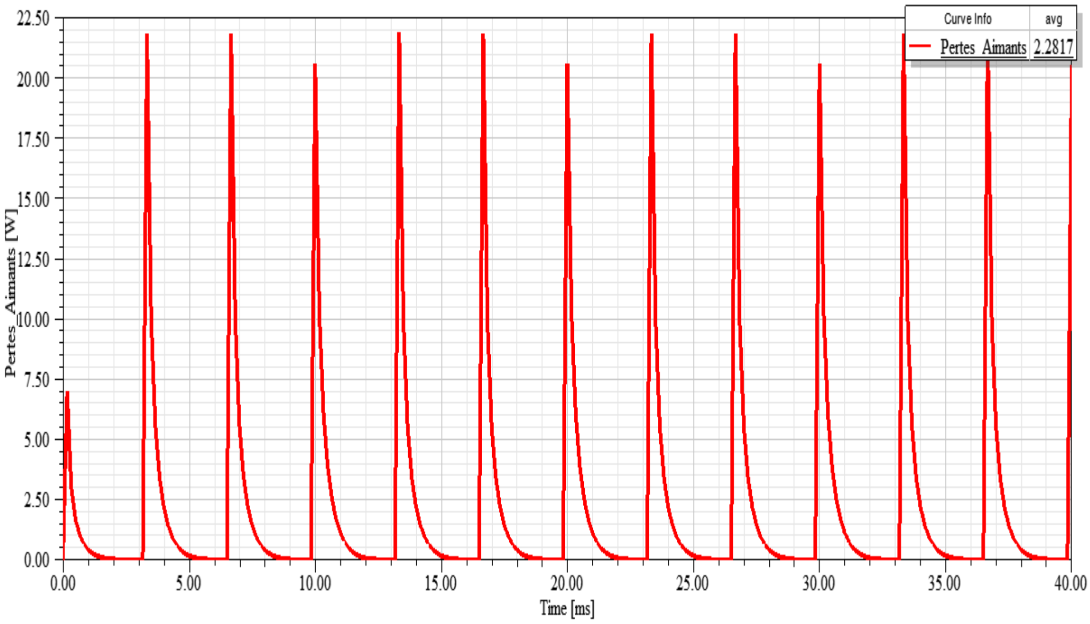

Figure 4: Losses in moving plate (PM).

The losses are obtain from integrating surface resistive heating over the area then multiplied by length of the generator, and calculating the average value in one period of time.

5. CONCLUSIONS

This paper details the calculation of the losses in the flat moving plate (rotor) using finite element methods in Linear Parallelepipedic Electric Machine. The different sources of these losses were outlined and divided into several categories. After the identification of the losses, their calculation was approached. The precision of the results and the time consumption are the compromises of the PMs eddy-current loss computation.

Losses in permanent magnets are quadratically dependent on its thickness. The overall value of losses in permanent magnets is the sum of losses due to slots effects and space-time harmonics of the magnetomotive force of the stator winding. Finite Element Method allows more accuracy results, but with a greater time consumption. One of the consequences of eddy-currents in permanent magnets is their demagnetization by a high temperature. Thereby, loss reduction by limiting these eddy-currents is necessary. The permanent magnets loss measurement is very difficult because the collective losses separation is not easy. The most common methods to perform the measurement of losses are collective losses separation and thermometric methods.

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