Slots Geometry Influence on the Air gap Magnetic Field Distribution

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Abstract: - Prediction and performance analysis of electrical machines depend mainly on the accuracy in the evaluation of the magnetic field linking the different parts of the machine. This paper presents the influence of the slots geometry on permanent magnet synchronous machine (PMSM) magnetic field distribution using finite element method (FEM), where we change the slots structure in order to improve the air gap magnetic field distribution .The accuracy of the developed model is verified by comparing its results with those obtained from experimental measurements.

Key-Words: - Air-gap, slots effects, finite element, magnetic field, permanent-magnet, synchronous motor.

1 Introduction

Permanent magnet synchronous motors (PMSM) are widely used in many industrial applications for their compactness, highly efficient and high torque density. As their cost continues to decrease they have the opportunity to become a dominant force in the industrial applications market. The pulsating torque which is inherent in their design it is one of the most important problems in permanent magnet (PM) motors. This ripple is parasitic, and can lead to mechanical vibration, acoustic noise, and problems in drive systems [1]. The electromagnetic torque developed by permanent-magnet machine and consequently both the average and pulsating torques in PMSM are mainly affected by the fluctuations of the field distribution, which depend on the magnet configuration and stator the slots [2].

Several research have studied the influence of these parameters on the form of the air gap magnetic flux and they have proposed various methods which take into account the magnet configuration , the direction of magnetization of the magnet bars along a magnet pole arc, the shape of stator slots and their number, the air-gap length, and the number of poles is essential to obtain the magnetic flux that won't cause problems to our machine and will give accurate analysis of the machine’s performances.

The evaluation of the performances of synchronous machine in static regime, based on the analysis of the different operating characteristics, can’t be achieved in PMSM because of the lack of the control of their excitation field. Therefore in order to compensate the lack of information regarding the determination of the shape of the air gap magnetic field distribution, we must use numerical solution.

During the last two decades the finite element method proved to be the most appropriate numerical method in terms of modeling, flexibility and accuracy to solve the nonlinear Poisson’s equation governing the magnetic field in electric machines [3,4]. Currently, several modeling of electrical machines softwares are available. The finite element package FEMM 4.2 (Finite Element Method Magnetic) developed by D.Meeker available for free on its website was used for the modeling of the PMSM.

In this paper we will present the influence of the slots design for air gap magnetic field distribution in PMSM as we modified the slots shapes in order to minimize their harmonics. This design is with fem. It is quite obvious that the results reliability of the numerical solution will have to be reinforced by experimental [5] results.

2 Poisson Equation of Magnetic Field

The formulation for magnetic field in quasi-static regime formulated using the magnetic vector potential $\vec{A}$ is represented by Maxwell's equations:

$\nabla \times \vec{A} = \vec{B}$ ... (05)

$\nabla \cdot \vec{B} = 0$ ... (06)

$\nabla \times \vec{H} = \vec{J}$ ... (07)

$\vec{B} = \mu \vec{H}$ ... (08)

The relation (6) states that the magnetic field $\vec{B}$ is solenoidal, while the relationship (7) which represents the Ampere in differential form defines the sources of the magnetic field in a medium of permeability μ.

The equation of the magnetic field $\vec{B}$expressed in terms of its sources is using:

$$\nabla \times \vec{H} = \nabla \times [\grave{v}]\vec{B} - \nabla \times [\grave{v}]\vec{M}_0 \quad \dots (9)$$

$$\nabla \times [\grave{v}]\vec{B} = \vec{J} + \nabla \times [\grave{v}]\vec{M}_0 = \vec{J} + \vec{J}_m$$

The permanent magnet is represented by a surface current density $\vec{J}_m$ which equivalent intensity is calculated using Stokes' theorem [4,7].

$$I_m = \oiint_{\Omega(\Gamma)} \vec{J}_m \bullet d\vec{\Omega} = \oint_{\Gamma(\Omega)} [v]\vec{M}_0 \bullet d\vec{\Gamma} = \oint_{\Gamma(\Omega)} \grave{v}_x M_{0x} dx + \grave{v}_y M_{0y} dy \quad \dots (10)$$

In Two-dimensional Poisson equation (9) becomes:

$$\nabla \times [\grave{v}]\vec{B} = \vec{k}\left[\frac{\partial}{\partial x}(\grave{v}_y B_y) - \frac{\partial}{\partial y}(\grave{v}_x B_x)\right] = (J + J_m)\vec{k} \quad \dots (11)$$

Finally the formulation of the magnetostatic field expressed using the vector potential is:

$$\frac{\partial}{\partial x}\left(v_y \frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(v_x \frac{\partial A}{\partial y}\right) = -(J + J_m) \quad \dots (12)$$

Where:

$\Omega(\Gamma)$ domain solution bounded by the contour Γ

J current density of the carrying current conductors

v peripheral speed of the rotor

H field intensity

M magnetization

M_0 magnetization constant

μ_0 permeability of free space

v_x and v_y are reluctivity of the medium and take the value of $\grave{v}_x$ and $\grave{v}_y$ within the permanent magnet

3 Main dimensions and Topology of Studied Machine

The studied machine is permanent magnet synchronous motor, with 3 phases, 4 poles, 36 slots in stator and with interior permanent magnet in the rotor, main dimensions and topology is presented in table 1 and figure 1 respectively:

Table 1. Main dimensions

Dimensions and material properties	Quantities
Outer diameter	60 mm
Stator inner diameter	40 mm
Rotor outside diameter	39.619mm
Number of magnets per pole	01
Number of pole	04
Number of slots	36
Number of conductors in series per phase	156
Stator resistance	0.378 Ohm
Rated power	990 W
Rated current	5.5 A
Rated speed	1500 tr/mn

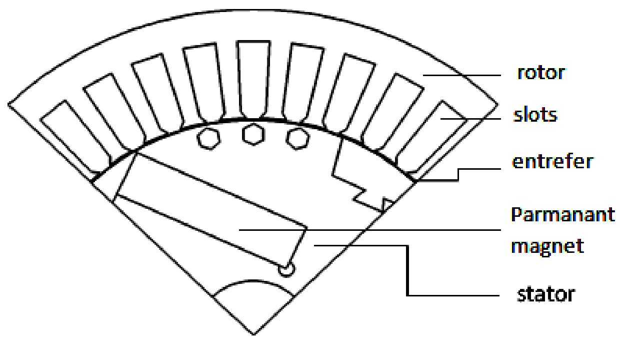

Fig.1, Topology of the machine

4 Magnetic field calculation with FEM

The finite element method is a numerical procedure designed to obtain an approximate solution to a variety of field problems governed by differential equations. The solution domain is replaced by the problem of the sub domains of simple geometric shapes, called elements, in order to reconstruct the original domain by their assembly. The unknown variables of the considered field are then expressed by an approximate function called interpolation function [6,7]. These functions are defined on each element using the values that the variable takes from the field on each node. Therefore the knowledge of nodal values and interpolation functions allow defining completely the behavior of the variable field on each element. Once the nodal variables, which are actually the unknown factors of the problem, are calculated, the values of the variables of the field on any point of the field can also be determined using interpolation function.

4.1 Modeling of the PMSM with FEM

Modeling of MSAP is to define the geometry, material properties of the magnetic circuit with their magnetization characteristics and the imposition of boundary conditions on the contour of the solution domain. By imposing the vector potential zero at the outside diameter of the machine the magnetic field will be confined to the solution domain, while the periodicity conditions $A(0) = A(\pi)$ can restrict the solution domain to a double pole pitch.

4.2 Magnetic Flux Results

The field solution was restricted to a double pole pitch because of the asymmetry introduced by the shape of the clamping retention of the magnets in their notches, various results can viewed as the mapping of field lines and the intensity of the magnetic induction in different parts of the machine as shown in Figure 1, however the main result of the simulation is the field distribution in the air gap which is given either in graphical form as shown in figures 2 or in the form of a table that provides the magnetic induction at a point as a function of the air gap of its curvilinear abscissa.

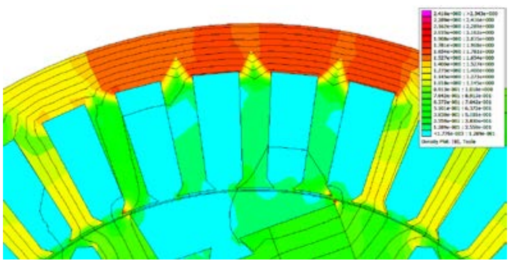

Fig.2, Magnetic flux distribution

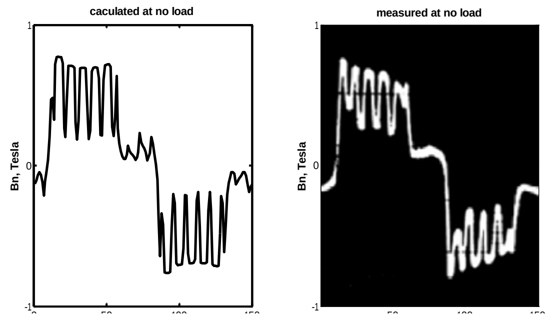

Fig.3, Magnetic field distribution along the air gap

Examination of these curves shows that rapid variations of the magnetic field are mainly due to the presence of teeth and slots of the stator area. Such variations are predictable because the calculation of the field using an interpolation function of the first order results in the constancy of the field [8,6] at each element of mesh. Moreover, the finite element solution is incomplete because the model is unable to take into account electromagnetic phenomena accompanying the rotation of the rotor. Indeed, in a real machine, the effect of oscillation of the field between the slots and teeth with induced eddy currents in the inner surfaces of the teeth, resulting in a local saturation of the interface zone air gap magnetic circuit [7]. For these reasons the field variations in a real machine are less pronounced.

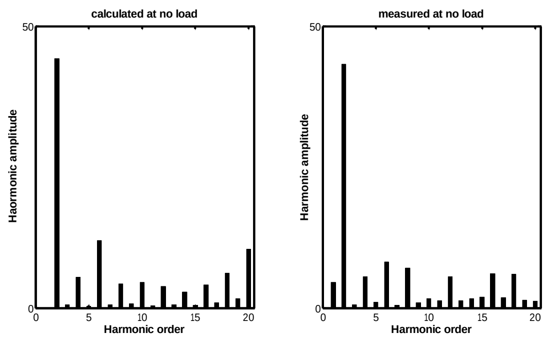

Fig. 4, Harmonic analysis of magnetic field distribution

It can be seen that the flux density waveforms are heavily polluted by the high order spatial harmonic. These harmonics are due to a slight asymmetry between the consecutive pair poles [9,10]. Their amplitudes are relatively small, but they still affect the shape of measured air gap waveform as far as comparison of the computed and measured flux density is concerned. Although the computed and measured value of the fundamental closely, some uncertainties remain concerning the evaluation of the high order harmonics because of the undesirable but inevitable slots effects, field oscillation and local saturation of the teeth [11-13]. These side effects have not only an impact on the amplitude spectrum leading to discrepancies between the measured and computed harmonics but also to tend to introduce an additional phase shift [9]. The later effect provides an indication on the magnetic state of the machine; the greater the phase shift is, the greater is the departure of the measured air gap flux density distribution from the computed ones.

5 Slots influence on Air Gap Magnetic Field

The illustrate of the slots effects on magnetic field distribution is the most important in this study The slots are simplified to a rectangular shape it based on the modified of the slots shape in order to minimize their harmonic, where the slot takes the form of a rectangle, as shown in the following Figure, it named modified slots type. The magnetic field is calculated in the proposed models. It is presented by diagrams and compared with precedent results of the magnetic field.

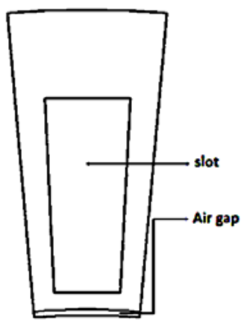

Fig.5, Modified slots types

5.1 Modeling results

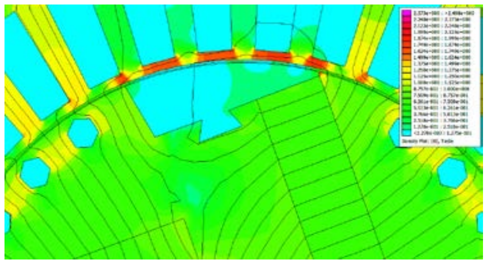

Fig.6, Magnetic flux distribution in the modified slots type

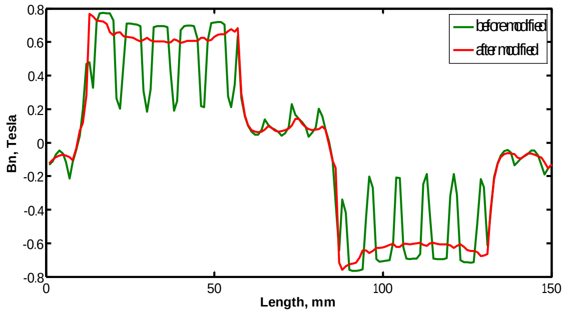

Fig.7, Air gap magnetic field distribution in the two slots types

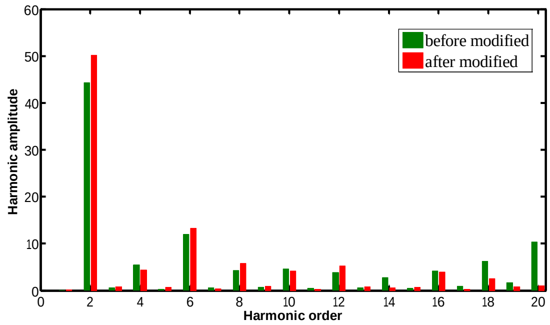

Fig.8, Harmonic analysis comparison of magnetic field in the two slots types

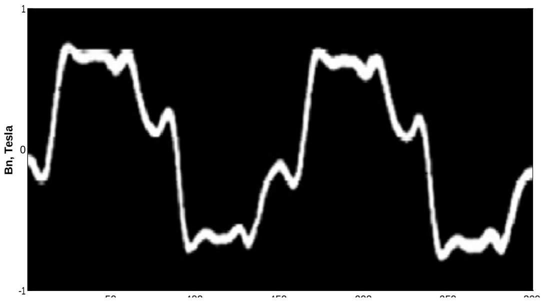

Fig.9, Filtered magnetic field measured

5.2 Discussion of results

From comparing the results:
we conclude that the depth in the magnetic air gap field distribution before modified slots are nearly eliminated after the modification of slots, this means that the harmonic slots are nearly eliminated and this is confirmed also in the harmonic analysis of the two types of magnetic field results.

6 Conclusion

As part of the determination and in order to improve of the magnetic field distribution in the gap of permanent magnet synchronous machines, a model with slots modified has been proposed. The finite element method was used to evaluate the magnetic field. From the comparison of results obtained, the proposed model to eliminate harmonic gives very good results model. Moreover a good agreement can be noticed between of the experimental results and of the numerical ones.

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