OPTIMIZATION OF STATOR SLOTS AND ROTOR VENTILATION HOLES IN PERMANENT MAGNET SYNCHRONOUS MOTOR

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Abstract— This paper describes a novel approach using a random optimization procedure to determine the design of a stator slots and rotor ventilation holes to obtain a maximum efficiency by reducing the losses in permanent magnet synchronous motor. We choose a model for coupled the magnetic and the electric geometry parameters to calculate the machine performance.

Index Terms— PMSM, Optimization, Stator slots, Rotor ventilation holes.

1. INTRODUCTION

THE Permanent magnets (PMs) are vital components of many electromechanical machines and electronic devices, but they are usually hidden in subassemblies. System designers and users often give no thought to how choice and use of the permanent magnet material affect performance, size, and cost of the product [1]. The concept of permanent magnet synchronous machines is not new. Since 1950, attempts have been made to employ permanent magnets in synchronous machines. However, those efforts were somewhat unsuccessful in the development of motors of substantial power ratings due to non-availability of high coercive force permanent magnets and relatively high unit cost. The stator of this machine is identical to that of a multiphase induction motor or electrically excited multiphase synchronous motor. The new component is rotor that in contrast to conventional synchronous machine rotors relies on permanent magnets as the source of excitation rather than an electric current in windings. The need of cage winding for line starting brings

conflicts in rotor design and restricts the choice of limited rotor geometries. The permanent magnet synchronous motor (PMSM) has the potential for energy saving in general applications such as fan, pump and compressor drives [2]-[3].
Interior permanent magnet synchronous motors (IPMSMs) are receiving increased attention for high performance drive applications because of their high power density, high efficiency and flux weakening capability. However, their high efficiency characteristic is influenced by applied control strategies. Thus much effort has been directed towards the efficiency optimization of the IPMSM by minimizing motor copper loss, this loss is influenced by machine parameters, thus online estimation of these parameters is essential. On the other hand the random is a tool for optimization and can be used for solving some problems that can be formulate in those forms that this algorithm can handle it [4]. In this paper we formulate nonlinear state equation of this motor in such form that we can use a random formulation for estimating the unknown parameters. Simulation results show that the estimated parameters converge to correct values after several iterations.

2. OPTIMIZATION APPROACH

The performance of a motor varies with many parameters, in particular its geometry parameters while the optimal design of the motor is influenced by further parameters such as the loss cost, production cost and per-unit price of iron and copper. The variation of each parameter influences differently on the performance of the motor. Therefore, numerous requirements, corresponding to different objective functions have to be full filled at a time. In this case a multi-objective optimization problem has to be solved. Usually, the minimum of a single objective function does not correspond to the minimum of each one of the other objective functions. Therefore a vectorial optimization takes place, namely a problem characterized by a vector of objectives, simultaneously depending on a set of design variables.
Fast development of computers enables the use of optimization methods in designing electrical machines today. Mathematicians are studying and developing new optimization methods like application of neural networks, fuzzy logic and genetic algorithm. The numerical solution of the magnetic

field in machine's core makes it possible to solve many problems accurately that is analytically impossible. Mathematically, the general non-linear multi variable constrained optimization problem can be stated as follows [5]:

$$Find: X = [x1, x2, ... xn] \quad (1)$$

such that $F = f(x)$ is minimum subject to:

$$xi_{\min} < xi < xi\max, i = 1,2,...., n \quad (2)$$

and

$$gi(x) < 0, i = 1,2,...., n \quad (3)$$

where $[x1, x2, ...xn]$ are the set of independent design variables with their lower and upper bounds as $xi_{\min}$ and $xi_{\max}$. $F = f(x)$ is the objective function to be optimized and $gi(x)$ are the constraints imposed on the design.

A. Optimization of stator slots

The geometry to be optimized is the stator slots of a permanent magnet synchronous motor as shown in Fig.1, for which the nonlinear analysis of magnetic field is carried out in using FEM. The finite element method is based on the resolution of Maxwell's equations. These equations play a fundamental role in the well established formulation of the electromagnetic theory. These equations lead to the derivation of precise mathematical models useful in many applications in physics and engineering. The Maxwell equations involve only the integer-order calculus and therefore it is natural that the resulting classical models adopted in electrical engineering reflect this perspective. Recently, a closer look of some phenomena present in electrical systems, such as motors, transformers and lines, and the motivation towards the development of comprehensive models, seen to point out the requirement for fractional calculus approach.

In an alternative perspective several authors have verified that well-known expressions for the magnetic potential are related through integer-order integral and derivatives and have proposed its generalization based on the concept of fractional-order poles. Nevertheless, the mathematical generalization towards calculus approach lacks a comprehensive method for its practical implementation. In the stationary coordinate system Maxwell's equations are always valid and expressed as follows:

$$\nabla \times \overline{E} = -\frac{\partial \overline{B}}{\partial t} \tag{4}$$

$$\nabla \times \overline{H} = \overline{J}_e + \overline{J} + \frac{\partial \overline{D}}{\partial t} \tag{5}$$

$$\nabla . \overline{D} = \rho_e \tag{6}$$

$$\nabla . \overline{B} = 0 \tag{7}$$

where:

$\overline{E}$ =The electric field intensity vector;
$\overline{B}$ =The magnetic flux density (induction) vector;
$\overline{H}$ =The magnetic field intensity vector;
$\overline{J}_e$ =The excitation (external) current density vector;
$\overline{J}$ =The induced current density vector;
$\overline{D}$ =The electric flux density (displacement) vector;
ρ_e =The external charge density.

In static and quasi-static (low frequency, less than 1.0 kHz) field problems, the displacement term in (5) is negligible. Therefore, (5) can be rewritten as follows:

$$\nabla \times \overline{H} = \overline{J}_e + \overline{J} \tag{8}$$

The magnetic field intensity $\overline{H}$ is related to the flux density $\overline{B}$ through the permeability μ as follows:

$$\overline{B} = \mu \, \overline{H} \tag{9}$$

In addition to the above equations a key variable, namely the magnetic vector potential $\overline{A}$, can be defined as follows:

$$\overline{B} = \nabla \times \overline{A} \tag{10}$$

Implementing the finite element discretization, using first or second order triangular elements, we can obtain the numerical solution. As a result of the finite element discretization, one obtains the following matrix equations for both the electromagnetic and mechanical problems:

$$[\mathbf{S}].[A] = [J_e] \tag{11}$$

and

$$[K].[U] = [F] \tag{12}$$

where:

S=Electromagnetic stiffness matrix;
K=Mechanical stiffness matrix;
F=Force vector.

If we solve (11) by using the Newton-Raphson method, we obtain the magnetic vector potential $\overline{A}$ [6]-[12].

The proposed method was employed in the optimization of stator slots of the motor. The initial suitable design sets for the first iteration are obtained from random method. (n) is the number of optimization parameters (n=3 in this work). The optimum slot shape was achieved and represented in Fig. 2.

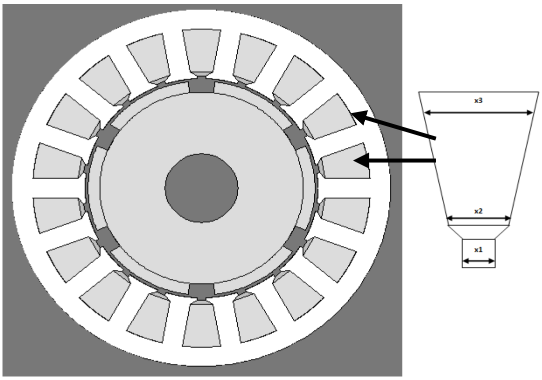

Fig. 1: Geometry of PMSM to be optimized

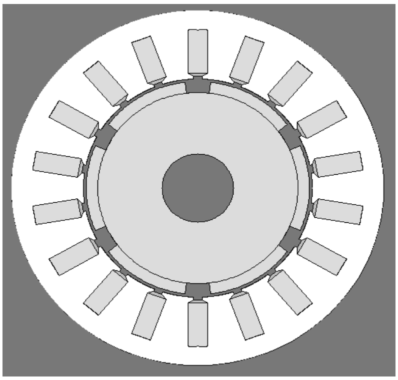

Fig.2: Geometry of PMSM after optimization

The variation of different components of losses in stator is represented in Fig. 3, in form of temperature. The design optimum set obtained from the random method is considered as the reference for the next approach of this work. It means the optimization of the ventilation holes in the rotor of this kind of machine.

(a) **(b)** **(c)**

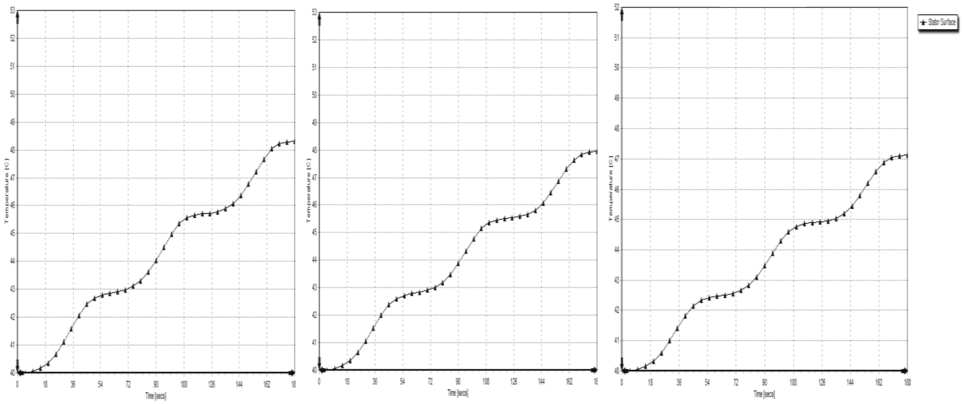

Fig. 3: Variation of temperatures in PMSM in the three steps of optimization

The values of the specifications of the motor are given in Table I.

TABLE I : VALUES OF VARIABLES IN THE OPTIMIZED MOTOR

Variables	(a) Initial value (mm)	(b) (n_i) Random iteration value (mm)	(c) Optimization value (mm)

x1	30	30	30
x2	58	50	31
x3	98	80	32

B. Optimization of rotor ventilation holes

The ventilation holes in the core of the inverter driven motor with high power, small size and light weight, should be designed for improving cooling capacity. To prevent temperature rise, ventilation holes are provided in the rotor-yoke. Ventilation holes have not only the direct radiating effect but also the ventilation effect in the air-gap by reducing airflow resistance. Moreover, ventilation holes have the role that lightens the weight of rotating machines. If we make the cross-area of the ventilation hole larger for cooling, however, the effective magnetic area becomes smaller, which results in the further magnetic saturation.

The magnetic saturation causes harmful influence on the fundamental component of the air-gap flux, which increases the magnetizing current and thus produces further temperature rise. Hence, it can be said that the compactness of motors makes the problem of the magnetic saturation more serious.

The temperature rise of the motor raises the resistance of stator winding, copper loss and destroys insulation of stator winding. Air-cooling system by fan is usually applied to prevent the temperature rise and ventilation holes in the core of the motor maximize the cooling efficiency. Since the ventilation holes magnetically prevent the flow of the magnetic flux, the magnetic resistance, magnetic flux density and core loss are raised. However, appropriate design of the ventilation holes cooled the winding, reduces the copper loss and eventually increases the efficiency. In this step, we investigate the relationship between the rotor-yoke configuration with ventilation holes and the magnetic flux density B in the air-gap, and perform a shape optimisation of ventilation holes. We applying the traditional design methodology, we determine the rotating machine model with the circle shaped ventilation holes, in which the various problems are practically resolved, and then by using the numerical analysis, we try to improve the configuration of ventilation holes from the viewpoint of the magnetic saturation. We perform an optimal design of the holes, which maximizes the ventilation effect without making the rotor-yoke saturation serious. We deal with the whole cross-area of ventilation holes as the objective function, and alter the shape of ventilation holes as the design parameter. As a constraint, we consider that the peak value of the fundamental component of the air-gap flux is kept constant. Moreover, as for the configuration of ventilation holes, the following conditions are assumed here:

(1) The shape of ventilation holes in the inner layer or outer layer is the same as each other;

(2) The center of each ventilation hole is fixed at the initial position;

(3) The cross-area of each ventilation hole is equal;

(4) The number of ventilation holes in each layer is constant.

The preliminary analysis indicates that the angular shape of ventilation holes causes the local magnetic saturation and thus the rounded shape is preferable. Therefore, we adopt ellipse shaped holes because of the easy manufacturing and the decrease of design variables. The design variables are a_{out}, b_{out}, a_{in} and b_{in}.

By using the design variables, the whole cross-area of ventilation holes S_{total}, i.e., the objective function is as follows:

$$S_{total} = N_{out}(\pi\, a_{out}\, b_{out}) + N_{in}(\pi\, a_{in}\, b_{in}) \tag{13}$$

Where N_{out} and N_{in} are the numbers of ventilation holes in the outer layer and inner layer respectively and Fig. 4 indicates the model to be optimized.

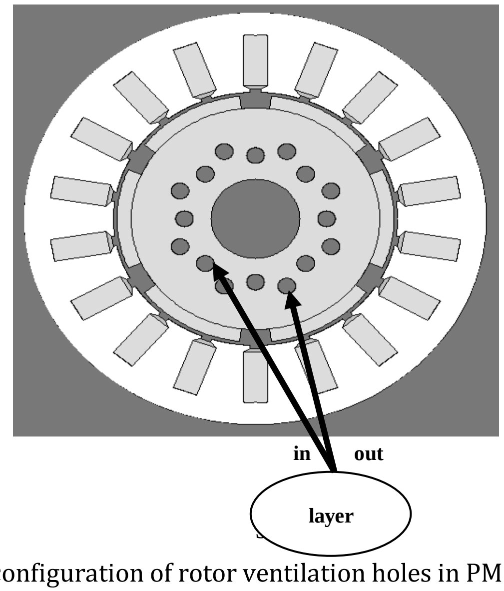

Fig. 4: The initial configuration of rotor ventilation holes in PMSM to be optimized

Figure 5 indicates the magnetic flux distribution of the initial configuration with the circle shaped ventilation holes. The flux density becomes high in the area between ventilation holes and the bottoms of permanent magnets, and between the ventilation holes near the traveling pole.

Therefore, the magnetic saturation in the area becomes more excessive. The space harmonics of the are-gap flux are caused by the local magnetic saturation of the rotor. This results in the noise, oscillation and the increase of iron losses and makes the peak value of the fundamental component of the air-gap flux lower. Thus, it is necessary to decrease the area where the flux distribution is dense. Instead, the area where the flux distribution is sparse such as the space between ventilation holes in the outer layer can be scraped. Judging from the results, it can be said that the shape of ventilation holes in the outer layer should become an ellipse with longer axis in the circumferential direction. On the other hand, as for the shape of ventilation holes in the inner layer, an ellipse with longer axis in the radius direction is preferable [10]-[18].

TABLE II: OPTIMIZATION RESULTS

Shape of ventilation holes	Design variable (mm) a_{in} b_{in}	Design variable (mm) a_{out} b_{out}	Cross-area of ventilation holes (mm^2)	Fundamental air-gap flux density (T)
Initial shape (circle)	11.00 11.00	11.00 11.00	6082.12 [100.00%]	0.86
Final shape	10.79 12.87	16.56 8.21	6907.10 [113.56%]	0.86

(ellipse)				

Figure 6 shows the flux density distribution of the optimized configuration. As the above-mentioned physical investigation, the shape of ventilation holes in the outer layer is optimized to be the ellipse with longer axis in the circumferential direction. As for the ventilation hole in the inner layer, the ellipse with a little longer axis in the radius direction is obtained. In the optimal configuration, the area where the flux distribution is not decreases as shown in Fig. 6, compared with the initial configuration but the cross-area of ventilation holes is increased. The results of both cases are shown in Table II.

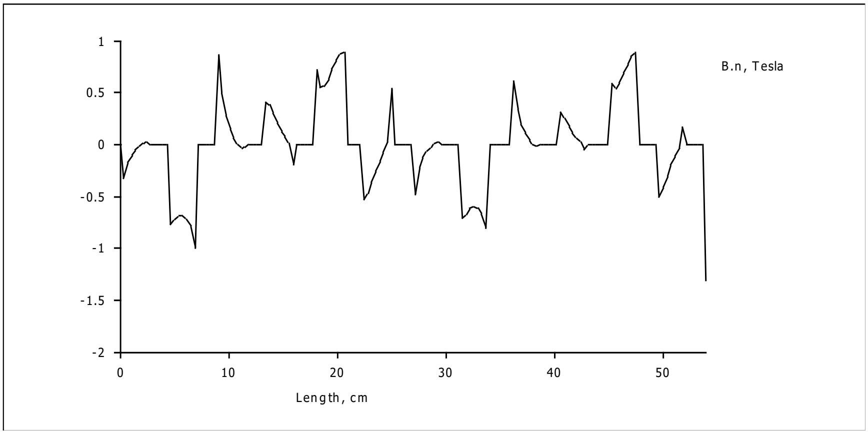

Fig. 5: Variation of the air-gap flux density
in the initial configuration

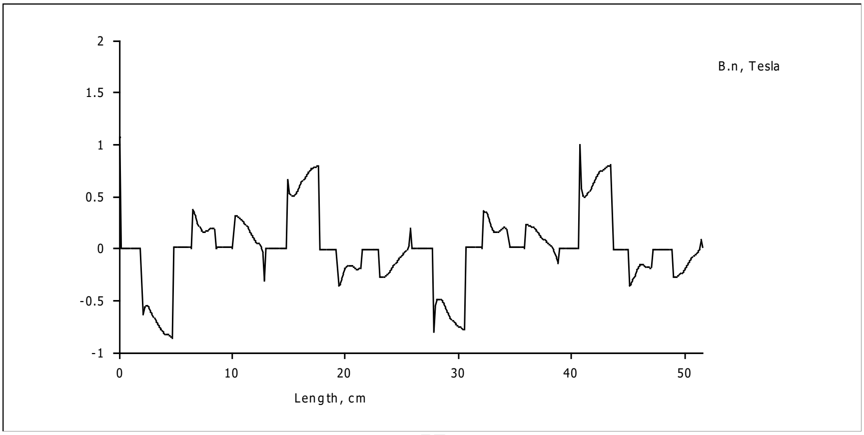

Fig. 6: Variation of the air-gap flux density
in the optimized configuration

The optimal design of electrical motors is a difficult problem in that:

1) it involves many variables which nonlinearly affects all the features and the behaviour of the electrical apparatus itself;
2) it needs the variables to be chosen in such a way that the design is feasible;
3) it often involves various conflicting objectives and goals.

For these reasons, the designer can profitably state the problem as a nonlinear programming problem able to deal with some or all the aforementioned difficulties and solve it with a suitable numerical optimization technique.

3. CONCLUSION

Optimization is intrinsically tied to our desire, we adjust some parameters to minimize or maximize our results and to do this, we use normally computer analysis to judge the quality of our design. In this work, we present a new method using a random optimization procedure to determine the design of a stator slots and rotor ventilation holes to obtain a maximum efficiency by reducing the losses in permanent magnet synchronous motor. A more complicated optimization can be carried out using a larger number of design parameters and more improvement may be expected.

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