

Application of New Tools in the Thermal Behaviour Study of Electrical Machines

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Abstract. Economic, competitive or energy efficiency factors require designing smaller and more efficient machines that pose greater demands on its design. This, coupled with the need to reduce time and production costs requires the use of simulation software as basic design tool. One of these requirements is to know the thermal behaviour of the machine, subject on which this paper focuses. Based on the electromagnetic study of permanent magnet synchronous machine (PMSM), performed using finite elements, a special attention is given to the calculation of iron losses that are later used to simulate its thermal behaviour. The results are compared with those obtained in real tests of the machine on steady states allowing validate the method, to later on, analyse the transient behaviour of the machine.

Key words

Thermal analysis, iron losses, permanent magnet, steady state, thermal model.

1. Introduction

The performance in industrial environments of any electrical machine is conditioned by a number of variables such as: electro-mechanical parameters, class of service, characteristics of isolation, type of construction, etc. One of these variables, and certainly not least important, is the thermal behaviour of the machine and which along with its electromagnetic behaviour –with which is closely related-, determines a good part of the industrial life of all electrical machine [1].

The thermal behaviour of the machine is specially important in the case of permanent magnet synchronous motors (PMSM) subjected in many of its applications to variable load conditions [2], and thus thermal stresses to which it is subjected represent a variation in the operating temperature of the magnets; this variation is an alteration in the magnets behaviour, that in the limit, can mean the loss of their magnetic properties [3].

Some time ago the classic design process for electrical machines was improved by the introduction in the process of calculation tools based on methods such as Finite Element; these tools allow a simulation of the behaviour of the machine previous to its construction. However, these help tools have focused mainly in their electromagnetic calculation, paying less attention to thermal design. This can be verified because the number of technical publications devoted to the electromagnetic study is considerably higher than those devoted to its thermal study [1]. This is largely due to the difficulty in defining the thermal circuit against the magnetic circuit, this happens because the heat transfer is performed by three different mechanisms: conduction, convection and radiation simultaneously.

In recent years there has been considerable progress in the development of increasingly compact Permanent Magnet Synchronous Motors (PMSM), which has allowed its introduction in applications impossible until that moment. This development is due to a combination of factors such as the improvement of permanent magnets or new manufacturing techniques [4], but also to the emergence of new tools for thermal design of them. Thus, in recent years has been an increase in technical publications devoted to study thermal machines [1-7] or a combination of thermal and magnetic studies [8, 9].

The main purpose of this paper is to present the process of analysis of a PMSM using electromagnetic and thermal design tools, relating the results of both and paying particular attention in the correct calculation of the magnetic losses in the machine stator which, given the nonsinusoidal flux evolution, the classic calculation shows lower value for the losses than the real ones.

2. Electromagnetic analysis

The machine analyzed in this study, designed for use in machine tool applications, is the kind of surface magnets having concentric stator winding and two parallel

circuits. Table I shows some of the main design parameters.

TABLE I. Details of the analyzed machine

Number of poles	8
Number of stator slots	36
Rotor outside diameter (mm)	104
Stator inner diameter (mm)	110
Stator outer diameter (mm)	180
Air gap (mm)	1
Magnetic steel type	M330-50A
Permanent magnet material	NdFeB
Thickness of the magnet (mm)	2
Angle of the magnets	37.5 °
Relative permeability	1.05
Remanent flux density (T)	1.155

For the electromagnetic analysis, given the symmetries of the machine, a 2D model of 180° has been used. Figure 1 shows the output of results in the distribution of magnetic flux density of the analyzed machine for a certain position of the rotor.

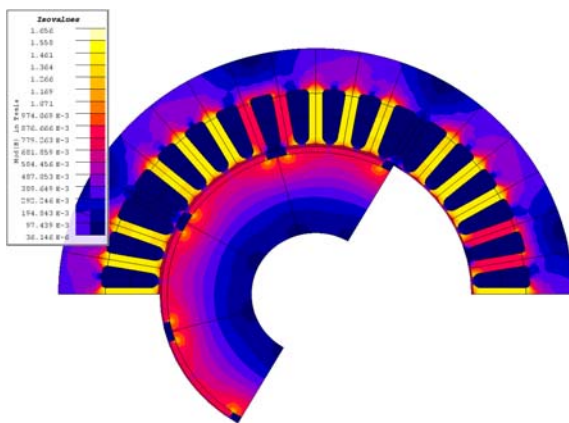


Fig. 1. Magnetic flux density.

The classical results of finite element analysis of a permanent magnet machine are distributions of flux, electromotive forces, torques, etc. however, for further thermal analysis of the machine, the main results are the sources of heat, which is the same, as the copper and iron losses.

3. Iron losses

The main reasons of heating in these machines are the Joule and iron losses; being the first ones easy to calculate -once known the composition of the winding and the current level of the machine-, the main problem is estimate the iron losses. Given the synchronous nature of these machines this losses focus almost exclusively on its stator, being its correct estimation of vital importance when studying the thermal behaviour of the machine. Typically, the finite element calculation software allow to estimate these losses for different regions of the machine, these estimates are based on the curves of loss (W/kg) of material used for the magnetic circuit, Fig. 2 shows this

curve for M330-50A type magnetic steel used in the studied machine.

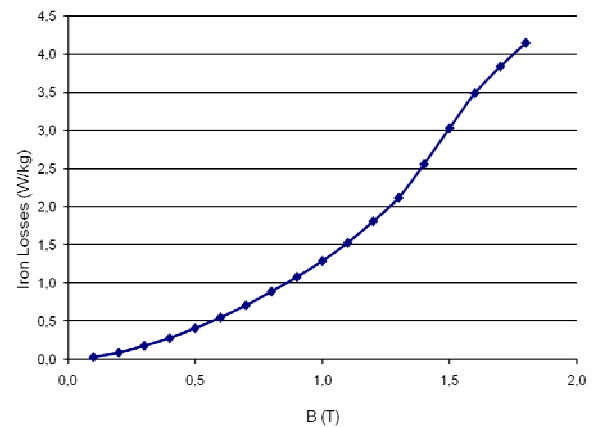


Fig. 2. Loss curve for the M330-50A magnetic steel.

An additional problem is that these curves are obtained by subjecting the material to test conditions; however, the actual operating conditions for the magnetic circuit of the machine are separated from the test ideal conditions when subjected to non-sinusoidal flux distribution. Trying to correct this problem, several authors [10-13] propose a method in which the total iron losses are separated into a hysteresis loss component (proportional to the area of the hysteresis loop of material) added to some dynamic losses:

$$P = P_h + P_d \quad (1)$$

The dynamic loss component is related to the distribution of magnetic domains in the material; the classical models assume a homogeneous distribution of domains in the material [10] and evaluate these losses by the expression:

$$P_d = P_c = \frac{\pi^2 \sigma d^2}{6} (B_m f)^2 \quad (2)$$

Being B_m the maximum value of induction, f the frequency, and σ and d the electrical conductivity and the thickness of magnetic material respectively. However, in the real case, this expression does not justify the total dynamic losses, showing then some excess losses that sometimes can be even higher than the classical losses [10], such excess losses are a function of f and B_m , according to the following expression [12]:

$$P_e = K (B_m f)^{3/2} \quad (3)$$

In this way, all of loss is based on three components of the form:

$$P = P_h + P_c + P_e \quad (4)$$

Following this theory, which is generally referred as Bertotti method, the FLUX software in its 10.3 version allow a better iron losses calculation under non sinusoidal

conditions using the following expression, where the three loss components mentioned before are included:

$$P=K_h B_m^2 f+\frac{\pi^2 \sigma d^2}{6}\left(B_m f\right)^2+K_e\left(B_m f\right)^{\frac{3}{2}} 8,67 \quad(5)$$

For the calculation, FLUX also employs the stacking factor of the magnetic steels, becoming the expression (5) as follows:

$$P=\left[K_h B_m^2 f+\frac{\pi^2 \sigma d^2}{6}\left(B_m f\right)^2+K_e\left(B_m f\right)^{\frac{3}{2}} 8,67\right] K_f \quad(6)$$

Where K_h and K_e are the factors of hysteresis and excess losses whose values should be calculated based on known data of the material loss curve. Once the K_h and K_e factors are calculated the initial loss curve can be adjusted to a new sum of the three aforementioned components, as shown in Fig. 3.

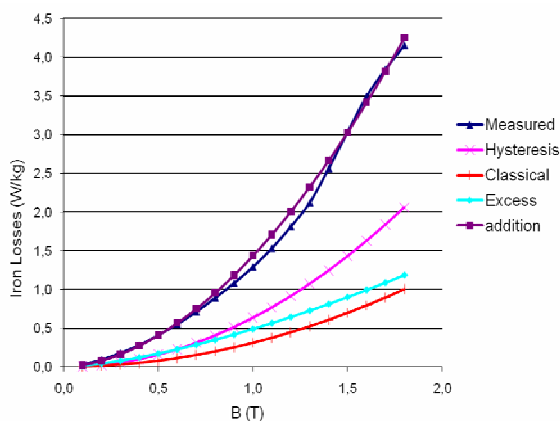


Fig. 3. Adjustment results by Bertotti.

Losses in machine stator have been calculated using this method for different speeds; also for later use in thermal simulation, total losses have been separated into the corresponding to stator teeth and crown of the machine. Table II shows the values of losses obtained in W, for speeds of 100, 1000 and 2000 rev/m.

TABLE II. Stator iron losses (W).

	Hysteresis	Classical	Excess	Totals
100 rev/m				
Teeth	1,019	0,145	0,447	1,613
Crown	0,390	0,043	0,228	0,662
1000 rev/m				
Teeth	1,746	13,220	13,350	28,326
Crown	0,667	4,096	6,972	11,736
2000 rev/m				
Teeth	4,080	57,564	39,399	101,044
Crown	9,380	17,339	20,383	47,103

Fig. 4 shows the evolution of the losses calculated, using this method, for different values of speed in the crown, teeth and total.

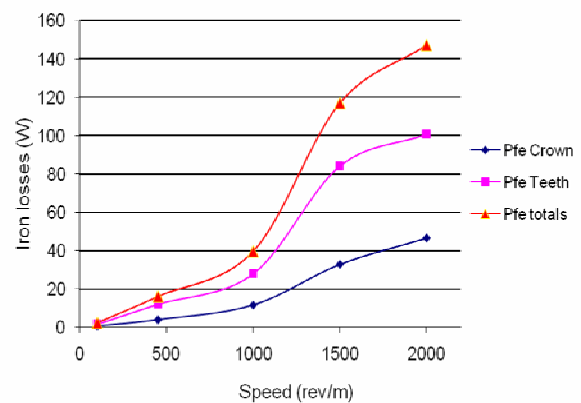


Fig. 4. Evolution of magnetic losses in the stator teeth, crown and total.

4. The thermal study

Thermal analysis is performed using the Motor-CAD software starting with the creation of a complete model of the machine, with radial and transverse representations, where all its dimensions and materials are introduced as well as the values of iron, copper and mechanical losses of the machine. Fig 5 shows a detail of these representations for the analyzed machine.

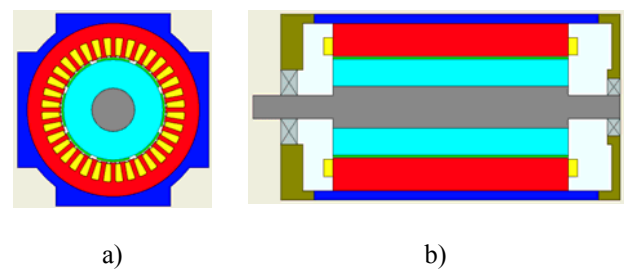


Fig.5. Radial and transverse representation of the analyzed machine.

The editor puts special attention on defining the winding of the machine in terms of number of layers, conductors per slot and the its section, or characteristic of the insulation between conductors to create from this the appropriate thermal model.

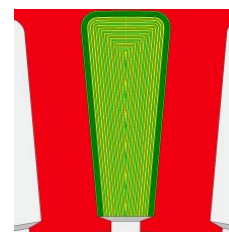


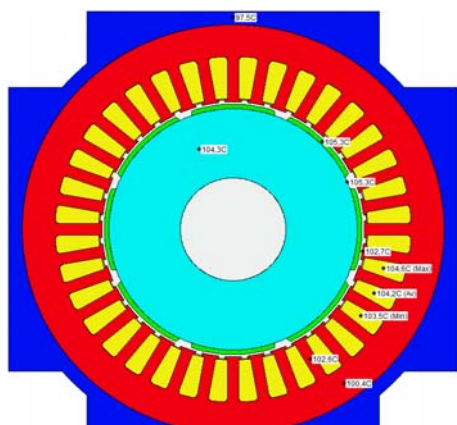
Fig.6. Thermal model of a stator slot.

A. Steady state analysis

Based on the provided data, the software creates a thermal model of the machine in lumped parameters showing the main sources of heat of the machine and the different paths for its transmission; in this model the thermal parameters of heat, thermal resistance or

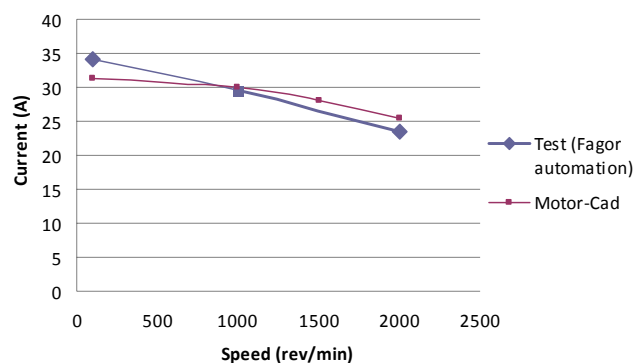
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From here, the software calculates the temperature (or temperature increases) in the different nodes of the model that correspond to different parts of the machine. The output results graphically are shown in Figures 8 and 9 for the radial and transverse representations of the machine.

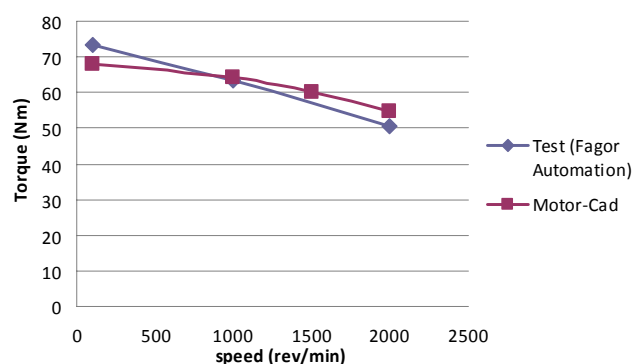


The results are compared with those obtained in real tests of the machine itself enabling validation of the method employed. The following figures relate current with speed and torque for temperature increases of 105° C for

Current vs Speed

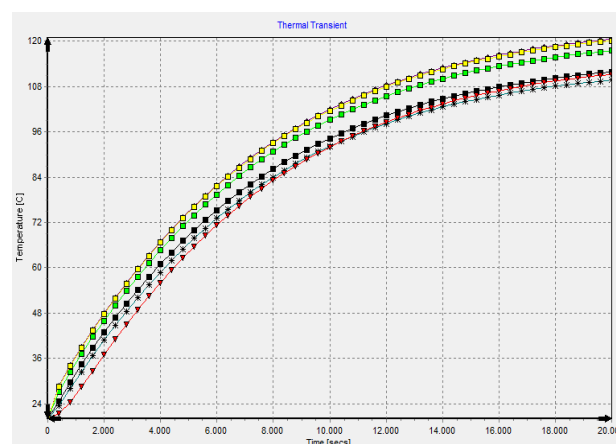


Torque vs Speed



B. Transient analysis

Besides the steady state analysis is also possible to analyse the behaviour of the machine in transient state, for which the model incorporates the machine's thermal capacities. Thus, is possible to analyse the thermal evolution of the machine from ambient temperature up to work temperature as shown in Fig. 11.



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And also variable load cycles can be programmed in order to analyse the behaviour of the machine under work conditions typically used in these machines. Fig. 12 shows the behaviour of the machine for a repetition of load cycles.

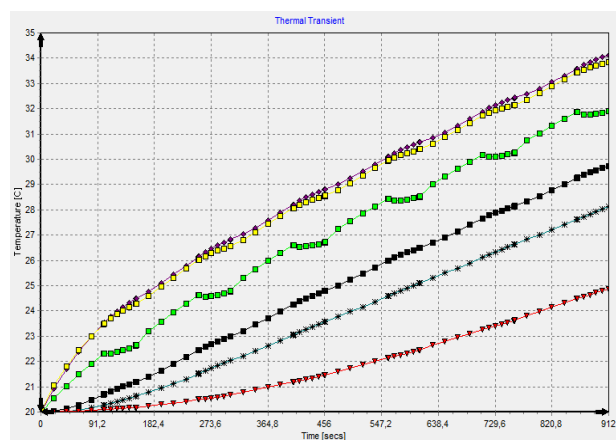


Fig.12. Thermal evolution of the machine under load variable conditions.

5. Conclusions

The performed comparison shows that the method can obtain satisfactory results in simulating the thermal behaviour of the machine, providing maximum difference of 8% in terms of necessary current values to achieve similar increases in temperature. Since the values used in MOTOR-CAD all come from simulation, these differences can be perfectly valid in the design process of the machine.

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