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Thermal Test Procedure and Analytical Model Calibration Method for Electrical Machines

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***Abstract*—In this paper a thermal test procedure and a calibration method for lumped parameter models are presented. Analytical models provide fast thermal simulations in comparison with finite element methods (FEM) and computed fluid dynamics (CFD) simulations. *Motor-CAD* is a useful and easy configurable tool to simulate motor models, but the quantity of construction parameters makes difficult the calibration process of a model. This paper provides a thermal test process to test machines to calibrate analytical models. And the procedure to estimate temperatures and calculate their uncertainties is exposed. Also a calibration method is proposed to identify critical parameters on analytical models that determine thermal behaviour of the machine. Specific thermal test are designed in order to calibrate these critical parameters like the base in the test bench. Finally the calibration process is validated with 3 different but similar machines. The same analytic model with only construction differences satisfies experimental thermal tests of 3 machines.**

***Index Terms*—Electrical, machine, magnet, thermal, model, analytical, Motor-CAD, calibration, test.**

I. Introduction

THERMAL ANALYSIS of electrical machines has become a necessary stage in the design process [1–3]. As important as the electromagnetic analysis, the thermal behaviour of the machine limits the efficiency and torque density. Losses reduce the transmitted energy and increase the working temperature. Typically thermal performances have been improved increasing the volume of the machine but it is well known that this solution may increase the cost. In addition in many applications such as traction system drives lighter motors are required and free space for electrical motors is reduced so that increasing the volume of electrical machine is not allowed [4–7].

The thermal analysis exposed in this paper is focused on Permanent Magnet Synchronous Machines (PMSM), so the most important temperature limit is on the magnets to prevent their demagnetization. Also, in these machines, the thermal behaviour causes a chain reaction that increases the work temperature. On the one hand, winding losses generate a rise in the temperature and the electrical resistance grows. So the power losses become bigger proportionally. On the other hand, the rise in the magnet temperature reduces the remanent flux density and more current is necessary to preserve the torque generation. And this would lead to a quadratic increase in winding losses.

Analytical models based on lumped parameter models are commonly used to reproduce the thermal behaviour of the machine [1–3], [8–22], and design the flow distribution in the cooling system [23]. Electrical similarities are made to study heat transfer, temperature is represented as voltage, thermal resistance corresponds to electric resistance, and the power losses are injected into the model as current supplies. A lumped parameter model is a network with nodes that represent parts of the machine with the same temperature. Nodes are connected with resistances that limit the heat transfer, and power losses are injected in nodes.

In this paper *Motor-CAD* (*Motor Design Ltd*) software has been used to define lumped parameter models [1], [16], [18–21]. In [1] an introduction to this software can be found. *Motor-CAD* is a useful tool at the analytical stage in the design process, because of the few resources that are required to predict temperatures. Comparing with Computational Fluid Dynamics (CFD) and Finite Elements Methods (FEM), analytical tools reduce computational time and memory requirements, as it reduces the nodes to calculate heat transfer. Also *Motor-CAD* has an extensive database with typical configurations to define geometries, materials and refrigeration methods, so it is easy to configure a machine without knowing thermal characteristics of the materials or the detailed 3D model.

The main difficulty configuring a machine on *Motor-CAD* is to know some parameters like air spaces inside the machine [15], some geometrical shapes not defined in the analytical software, convection coefficients, radiation emissivity or impregnation qualities. Air spaces in the windings, between materials or in the end-space, reduce the heat transfer due to the low thermal conductivity of the air.

The main goal of this paper is to identify the influence of some parameters in the thermal behaviour of the machine and to propose a calibration method to configure the key parameters of the model based on experimental results.

II. ANALYTICAL MODELS FOR THERMAL ANALYSIS

In this section the analytical model on *Motor-CAD* and the procedure to obtain the experimental temperatures that calibrate the model, will be explained.

A. Introduction to the analytical model

The motor calibrated with the proposed procedure is an enclosed machine with interior rotor, and without forced ventilation. Also there is not housing, so the stator lamination, the end-caps and the base dissipate power losses by natural convection.

The lumped parameter model used is shown in fig. 1; it is an axial view of the machine. At the bottom are the shaft, the rotor lamination and the magnets. In the middle there are the winding and the end-windings, and the stator lamination. At the top of the schematic there is the base in the centre, and the end-caps on the corners.

B. Experimental temperatures to compare

The temperatures obtained from experimental test are the output parameters of the analytical simulations, with energy losses as input parameters in the model. The temperatures that will be compared are the average temperature in the winding and the average temperature in magnets.

Because the temperature measure inside machines can be different depending on the position where it is measured. Fig. 2 shows the temperature of the winding and the magnetic steels on 3 different slots of a machine. In the same slot there is shown a variation of 10 K, and there is 8 K variation between different slots. The end-windings were almost at the same temperature than winding inside the slot, so they are not shown in the figure. In addition analytical simulations provides averages and maximum temperatures, but not geometrical distribution. Also in totally enclosed machines with interior rotor, it is not easy to measure temperature in magnets.

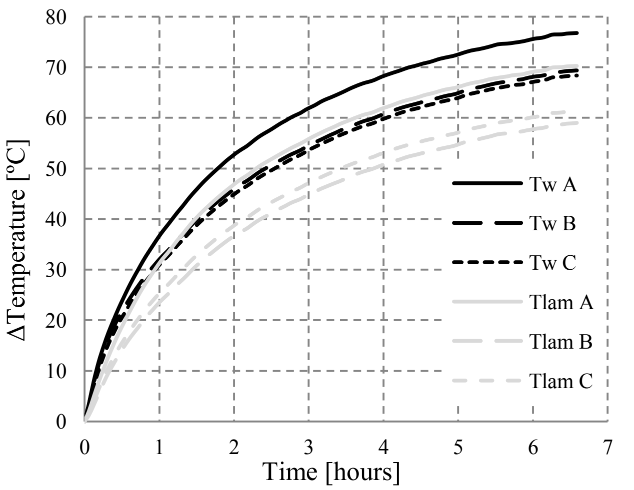

Fig. 2. Temperature evolution inside 3 different slots (*A*, *B* and *C*) in the winding (*Tw*) and lamination (*Tlam*)

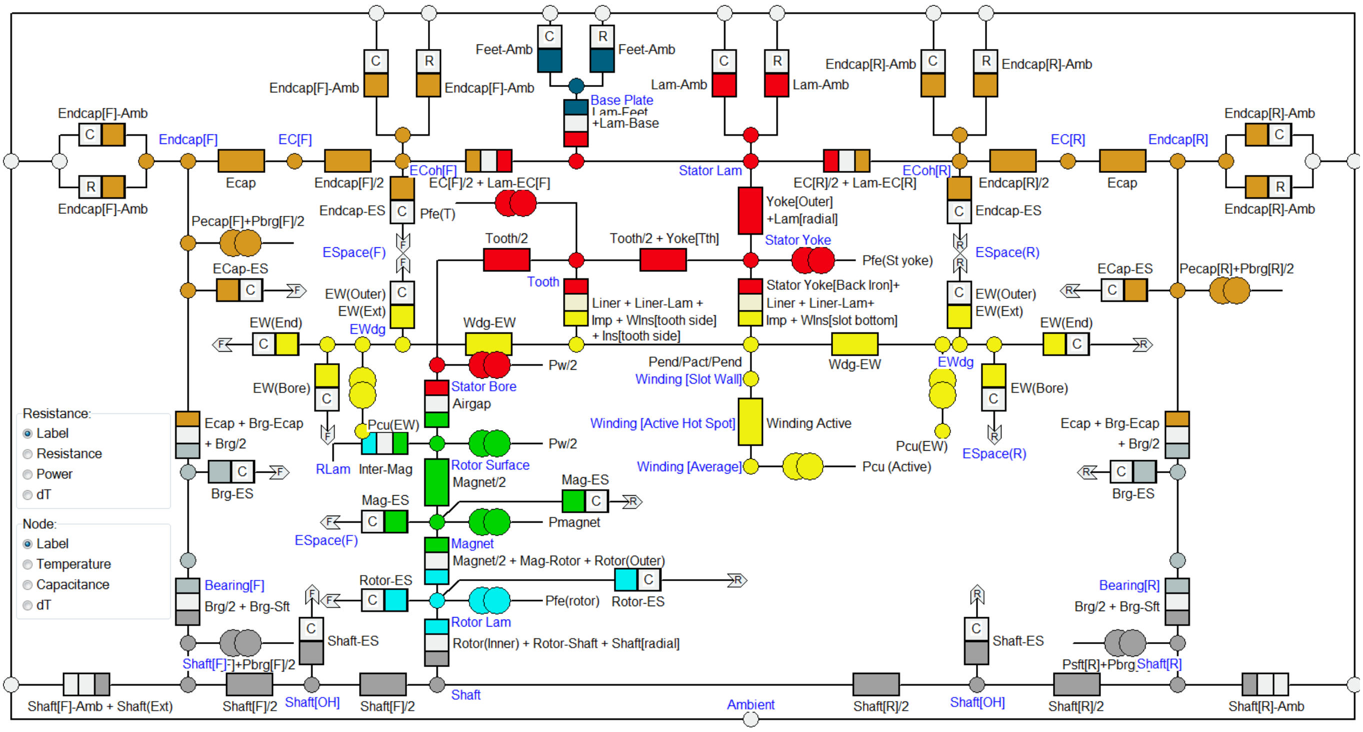

Fig. 1. Lumped parameter model simulated in *Motor-CAD* (*Motor Design Ltd*)

So the experimental temperatures to be compared will be estimated by winding resistance and flux density of the magnets. The increase in the temperature (ΔT_w and ΔT_m) will be estimated from winding resistance (R) increment and magnet flux density (B_r) decrease. In (1) and (2) thermal coefficients α and β are used.

$$\Delta T_w \beta = \frac{R}{R_0} - 1 \quad (1)$$

$$\Delta T_m \alpha = \frac{B_r}{B_{r0}} - 1 \quad (2)$$

III. Thermal Test Procedure

The thermal test procedure exposed in this section defines the way to test the motor, estimate the temperatures at the disconnection instant and determine the uncertainty on temperature estimation from R and B_r. Fig. 3 shows a flow chart with the thermal test procedure proposed on this section.

A. Thermal test protocol

The winding temperature estimation is based on its electric resistance increment due to an increase on its temperature. And the temperature on the magnets is estimated from back EMF because of the fall of flux density. So the first stage in the thermal test procedure are measurements of winding resistance and back EMF at room temperature. It is important to measure before connecting the motor to ensure room temperature within the machine.

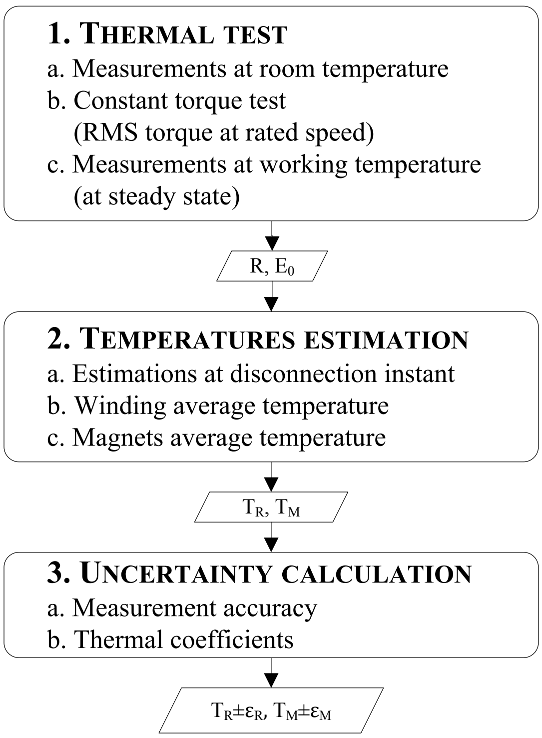

Fig. 3. Flow chart of the proposed thermal test procedure

When the values of winding resistance and back EMF are known at room temperature the thermal test starts. The main objective is to heat up the motor controlling test conditions to be able to simulate the thermal test with analytical models and calibrate them. So the test is at constant speed and current to control power losses. Also these test conditions must be similar to final application, so the values of speed and torque are RMS values. The load motor is configured to rotate at nominal speed and the test motor in constant current mode.

After reaching the thermal steady state, the load torque and the voltage supply are constant. Disconnect the motor and, as soon as possible, measure winding resistance and back EMF to calculate variations.

B. Temperature estimation at disconnection instant

After disconnecting the thermal test, the machine temperature falls and measurements don't correspond with working temperature.

International Standard [24] allows to estimate the temperature by the resistance method in machines of less than 50 Kw if it is measured in 30 seconds from disconnection instant. In case of more time until 60 seconds the value at the disconnection instant is estimated with a semi-logarithmic function.

In fig. 4 is shown the temperature on the winding and the magnets after a DC thermal test, captures have been made with intervals of 30 seconds. In the one hand, the winding cools down 5 ºC during the first minute and 3 ºC more during the 2nd minute. On the other hand, magnet temperature is almost constant during 15 minutes after disconnection.

So after the thermal test it is important to measure winding resistance as soon as possible and take different following values of time and resistance through 5 minutes with intervals of 15 seconds. In the machines tested in this study, the temperature at the disconnection instant is estimated assuming the temperature fall during the first minute to be 150% the fall during the second one. After that back EMF can be measured to estimate magnet temperature.

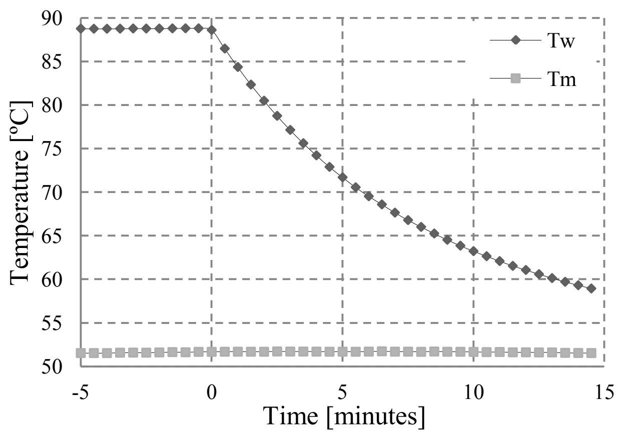

Fig. 4. Temperature evolution after thermal test in winding (*Tw*) and magnets (*Tm*)

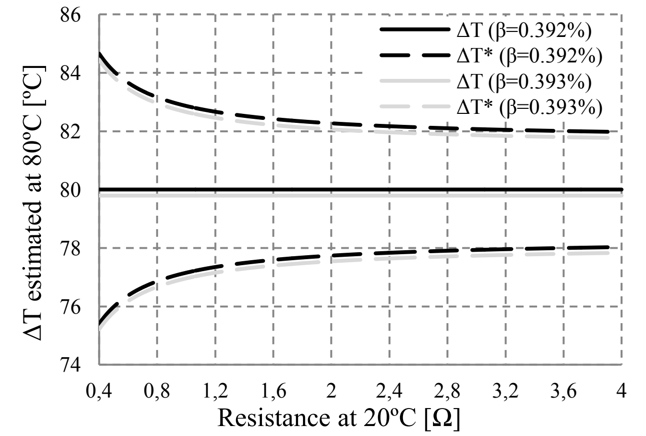

Fig. 5. Possible temperature estimations in the winding, due to errors in the copper thermal coefficient *β*

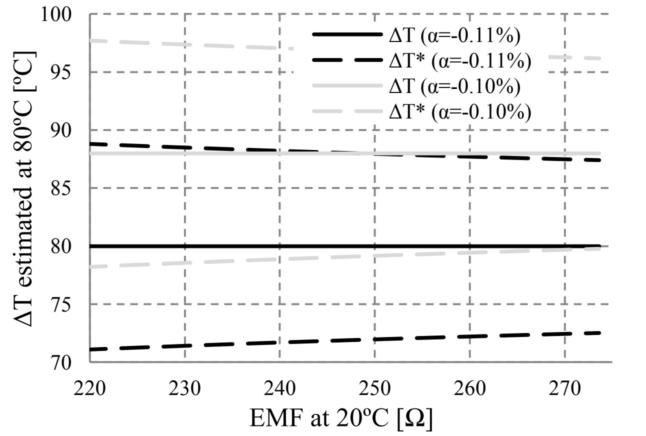

Fig. 6. Possible temperature estimations in the magnets, due to errors in the magnet thermal coefficient *α*

C. Uncertainty on temperature estimation

The third state in the thermal test is to enclose the estimations with possible errors to situate the calibration results. These errors come from precision errors on measuring instruments and coefficients *α, β* used on estimations (1) and (2).

Fig. 5 and fig. 6 show maximum and minimum possible estimations with tested machines when they have heat up 80 ºC. The worst cases with maximum error on estimation have been supposed when measuring a lower value of resistance at room temperature and a higher value at working temperature, or vice-versa.

The winding resistance has been measured with *Chauvin Arnoux 6240* micro-ohmmeter. In the scale 0.4 - 4 Ω the accuracy is 0.25%±2 mΩ, it is important to use the correct scale because the next scale has a resolution of 20 mΩ instead of 2 mΩ. In fig. 5 is shown the possible estimation due to the maximum possible errors for different values of resistance at room temperature. The possible deviation on β coefficient from 0.392% to 0.393%, that is typical on literature, is not a major problem.

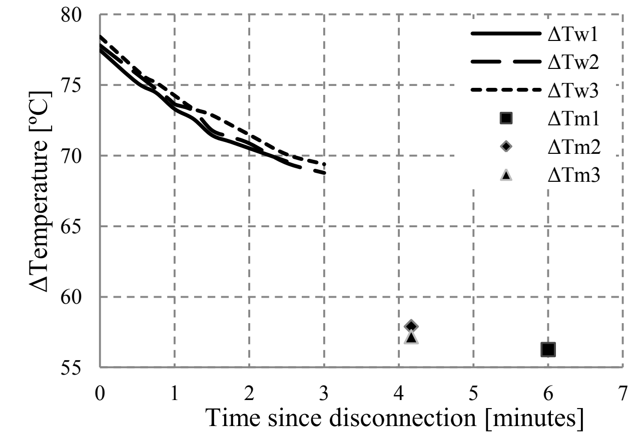

Fig. 7. Temperature in the winding (*ΔTw*) and magnets (*ΔTm*) of the same machine after 3 equal thermal tests

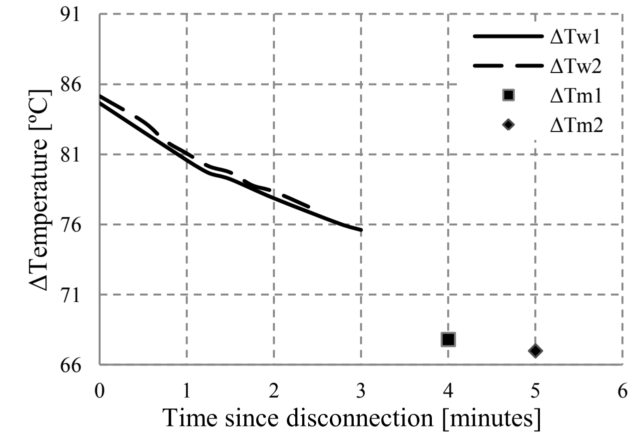

Fig. 8. Temperature in the winding (*ΔTw*) and magnets (*ΔTm*) of 2 identical machines after equal thermal tests

The back EMF is measured by using *Yokogawa WT1600* Digital Power Meter. In this case the voltage accuracy is 0.1%±1 V, and the thermal coefficient α to estimate the magnet temperature varies from -0.10% to -0.11%. Fig. 6 shows the possible estimations due to these 2 uncertainties.

In fig. 6 it is supposed a linear relationship between back EMF and B_r. But due to saturation effects it is necessary to estimate by FEM simulations the correct value of B_r according to the back EMF measured.

D. Thermal test results repeatability

The main objective of the thermal test is to provide the working temperature of the machine when operating under certain conditions to perform the characterization. So results from thermal test must be repetitive under the same conditions.

Fig. 7 shows the temperature evolution of a machine after 3 equal thermal tests and in fig. 8 two machines of the same model have been tested on equal thermal test. In two figures differences are less than the uncertainty in measurement, so results are repetitive.

As conclusion, on the one hand, the thermal test conditions are controlled and, on the other hand, there are not differences on thermal behaviour due to fabrication process (like air spaces o impregnation quality).

IV. Calibration Method

This section presents a calibration method to identify critical parameters in analytical models that determine the thermal behaviour. After that, specific thermal test are designed to calibrate them.

Analytical models are very useful due to the computational time, but in *Motor-CAD* there are many construction parameters and too many time can be spent calibrating all of them. *Motor-CAD* adjusts by default these parameters with typical values and they can be modified for a detailed modelling, and it is not always necessary. So it is necessary to identify critical parameters to begin the calibration process.

A. Description of the proposed method

In fig. 9 a flow chart present the proposed calibration method. It begins with a sensitivity analysis to identify the critical parameters, in machines tested on this work the base, and the natural convection and radiation coefficients, have been the most relevant ones. Once the critical parameters have been identified, specific thermal test are designed to adjust them, in this case different bases are calibrated. Finally the model is validated with experimental results.

B. Sensitivity analysis on Motor-CAD and Minitab

The sensitivity analysis consists in a sensitivity study on *Motor-CAD* and a statistical study with *Minitab* software. For this study 7 parameters shown on TABLE I are analyzed to identify their influence over thermal behaviour.

The natural convection coefficient can be found in the literature between 5 and 15 W/m^2/K, and *Motor-CAD* provides 5 as default. The emissivity coefficient is very dependent on surface material and finish. The base dissipates power due to the increment on the surface in contact with the ambient. The impregnation removes air spaces in the winding and is difficult to determine numerically the quality as consequence of the fabrication process. Rotational speed could determine heat transference inside the machine. And finally, there is an uncertainty on magnetic losses estimation, and their influence must be studied in the sensitivity analysis.

TABLE I
PARAMETERS IN THE SENSITIVITY ANALYSIS

	Parameter	Value1	Value2
A	**Convection coef.**	5	10
B	**Emissivity coef.**	0.2	0.8
C	**Base**	YES	NO
D	**Winding impreg.**	0.2	0.8
E	**End-winding impreg.**	YES	NO
F	**Rotational speed [rpm]**	200	400
G	**Magnetic Losses [%]**	100	150

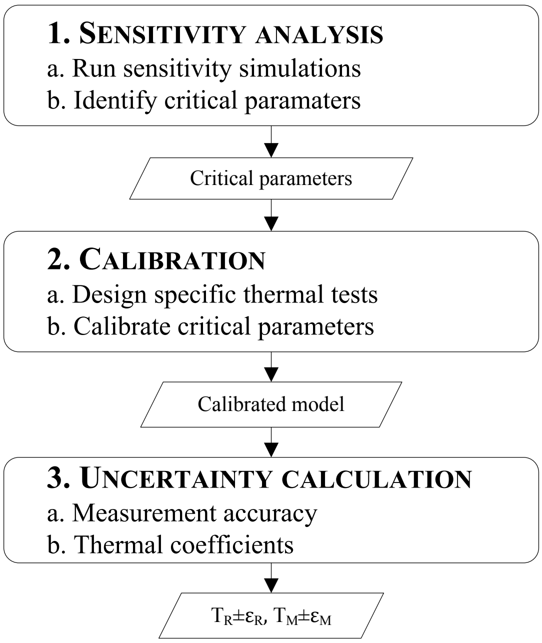

Fig. 9. Flow chart of the proposed model calibration

A sensitivity analysis is simulated in *Motor-CAD* with 2^7 combinations and temperatures obtained for magnets, winding, end-winding, and stator lamination are introduced in *Minitab* software. This statistical software provides the effect of each parameter on each temperature.

It has been seen that inside the machine 2 main temperatures can be distinguished, one in the winding, and another one in the interior parts of the machine. So at first approximation, in fig. 10 a simple thermal circuit describes: these 2 temperatures inside the machine, the thermal resistances that determine working temperatures, and winding losses that are dominant on these machines at low speeds.

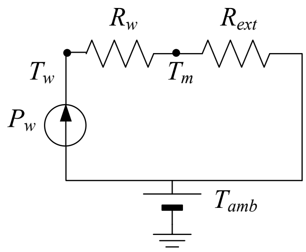

Fig. 10. Thermal resistance to the ambient (R_{ext}) and winding composition, air spaces... (R_w), determine winding and magnet temperatures (T_w, T_m) due to power joule losses in the winding (P_w)

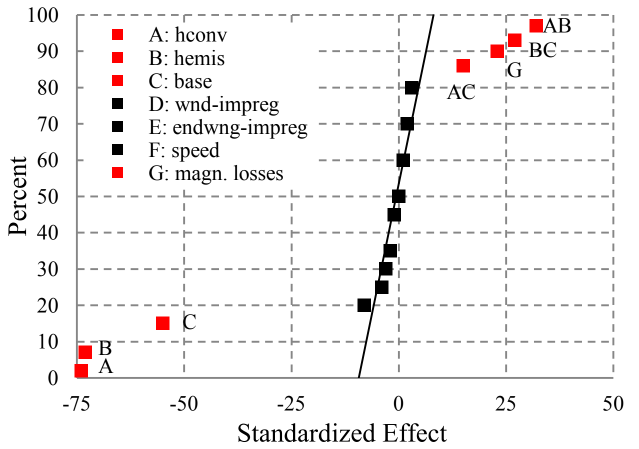

Fig. 11. Influence of parameters from sensitivity analysis on magnet temperature

On the other hand, *Minitab* software provides with fig. 11 the influence of the parameters on magnet temperature. This trend also occurs on the others temperatures but with smaller effect. Parameters further from the line have more influence on the temperature, so convection coefficient, emissivity coefficient and the base determine the interior temperature of the machine. Also an increment of 50% on magnetic losses increases magnet temperature.

As conclusion of the sensitivity analysis, the interior temperature of the machine can be calibrated adjusting the external dissipation (convection heat transfer, radiation emissivity and base configuration). And after that, the winding configuration inside slots determines winding temperature and consequently the thermal jump between winding and magnets, fig. 10.

C. *Practical implementation*

Once known critical parameters on tested machine, natural convection and emissivity are adjusted with values form literature and the main unknown is the base configuration.

Fig. 12. Wood and Aluminium bases for base calibration

Fig. 13. Test bench base, complex shape to model in *Motor-CAD*

To calibrate the base where the machine is placed, 3 thermal tests are designed. The tested machine has concentrated winding, 7 Kw mechanical power, 383 rpm and 16 A nominal current. The thermal tests compare the working temperature on 3 different bases with 8 A DC supply:

- Wood base: Model without base, fig. 12
- Aluminium rectangular base: Good thermal conductivity and known dimensions, fig. 12
- Test bench: main goal of the calibration, and difficult to model due to complex shape, fig. 13

DC thermal test provides mobility to test the machine without base to mount it, and suppresses the uncertainty due to magnetic losses affecting the thermal behaviour.

Fig. 14 shows the comparison between thermal results obtained in *Motor-CAD* and experimental measures of the 3 thermal tests. In the graph the lines represent the dynamic of transient simulations and symbols are individual measurements during the thermal test.

The test without base results in a higher working temperature. The test on the aluminium base is configured in *Motor-CAD* with 1.5 metres long and 0.4 metres width, and an emissivity factor of 0.03 due to polish finish. The test bench has been configured 1 meter long and 0.3 metres width, and emissivity factor of 0.1, taking into account a small base that connects the motor with the test bench.

Adjusting 3 different bases to calibrate the magnet temperature, the winding position inside the slots has been defined with the liner-lamination gap as 1.4 mm. This parameter adjusts the thermal jump between winding and magnets, as well as the winding temperature.

As conclusion of the practical implementation, in fig. 14 difference between results from simulations in *Motor-CAD* and experimental measurements is less than uncertainty estimation explained before. So results are accepted as valid.

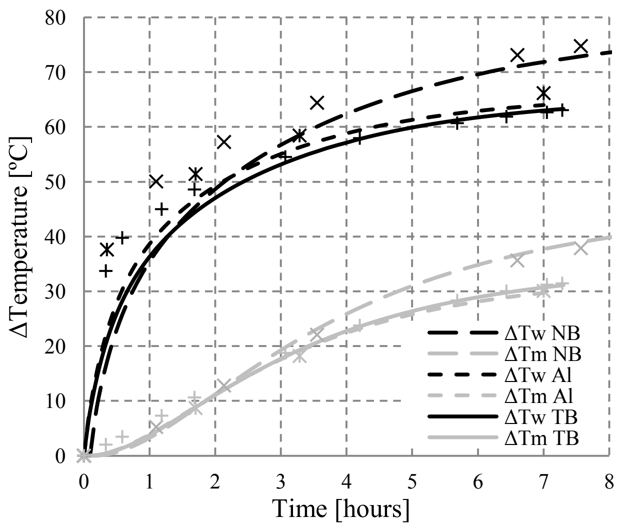

Fig. 14. Experimental validation of winding and magnet temperature increases (*ΔTw*, *ΔTm*) different bases: *No Base*, *Aluminium base*, and *Test-Bench base*. (Continuous lines show simulation results, and marks are experimental estimations during thermal tests)

V. Experimental Validation of the Proposed Method

In this paper 2 procedures have been proposed to run thermal test and calibrate analytical models on *Motor-CAD* software. After indentifying critical parameters in analytical model, specific thermal test have been designed and calibration has been realized.

The posterior validation process is focused on 3 similar machines with interior rotor and permanent magnets. Physically these machines are enclosed by end-caps enclosing the air around the rotor and end-windings. There is not housing and the stator lamination dissipate directly the heat to the ambient.

The objective of the experimental validation is to validate the analytic model in *Motor-CAD* with similar but different motors. Three machines are calibrated with the proposed method in *Motor-CAD*. The first one has been analysed in the practical implementation of the method, the second one is similar but it has distributed winding, and the third one, also with distributed winding, is a twice longer than the other 2 machines.

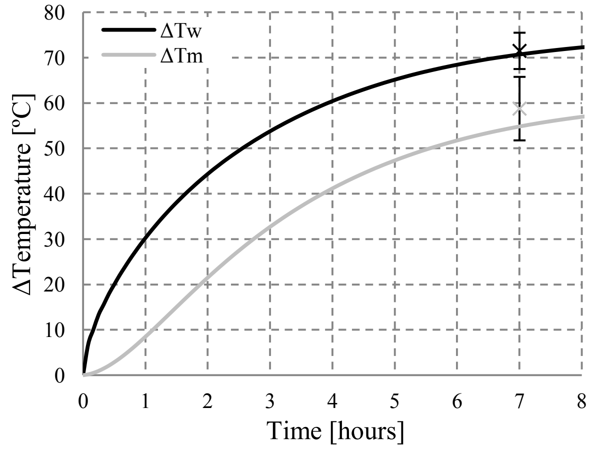

Fig. 15. Experimental validation of winding and magnet temperature increases (*ΔTw*, *ΔTm*) of M2 machine, 290 mm long, distributed winding. (Continuous lines show simulation results, and marks are experimental estimations with uncertainty estimation)

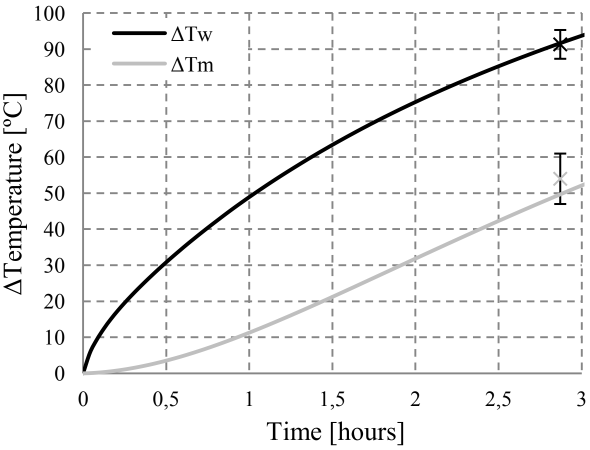

Fig. 16. Experimental validation of winding and magnet temperature increases (*ΔTw*, *ΔTm*) of M3 machine, 465 mm long, distributed winding. (Continuous lines show simulation results, and marks are experimental estimations with uncertainty estimation)

TABLE II
Custom Parameters of Each Analytical Model

Parameter	M1	M2	M3
Slots	18	48	48
Poles	16	16	16
Length	290	290	465
Conductor/Slot	328	138	132
$P_{winding}$	222	246	729
$P_{magnetic}$	0	77	76
Base Width	300	400	300
Base Length	1000	300	500
Liner-Lamination gap	1.4	0.7	1

TABLE II shows the parameters customized on each analytical model simulated in *Motor-CAD*. In grey are specific parameters of the motor, and then base dimensions of each motor and the liner-lamination gap that determine the winding position in slots.

As result of the calibration method fig. 14, fig. 15, and fig. 16 show comparison between *Motor-CAD* simulations and experimental measures. Differences between simulations and thermal test are smaller than measurement uncertainties, so results are taken as valid.

VI. Conclusions

In this work a detailed calibration method for thermal lumped parameters models is proposed. In combination with this method a thermal test procedure to obtain critical working temperatures is presented as well. After a short review in different tools for thermal design and analysis of electrical machines, lumped parameter models have been found to be flexible and with low computational load. For this purpose *Motor-CAD* has been proved to be a useful tool to create the thermal models and simulate them.

A thermal test procedure has been presented to estimate the winding and magnet temperatures, which are critical temperatures in these machines. Temperatures are not directly measured by thermocouples but they are estimated from winding resistance and back EMF measurements. After performing thermal tests it has been found that winding temperature can vary about 15 ºC depending on the position of thermocouples,. In addition as the motor is totally enclosed it is rather complicated to measure magnet temperatures by thermocouples. The uncertainties on temperature estimations due to instrumental precision and thermal coefficients have been calculated. For winding temperature the uncertainty can be up to ±4 ºC due to instrumental precision. Regarding to magnets temperature the uncertainty is about 8 ºC due to instrumentation accuracy,plus another 7 ºC due to the variation in thermal coefficient of magnets.

A sensitivity analysis of thermal simulations with *Motor-CAD* has been performed and critical parameters have been identified. On the one hand the average temperature of the motor depends mainly on the convection and radiation heat transfer, and on the base dimensions as well. On the other hand winding temperature depends on the impregnation goodness and air spaces inside slots. So a calibration method to determine these critical parameters has been exposed and validated. Three thermal simulations satisfy experimental results taking into account the uncertainty on temperature estimations.

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VIII. Biografies

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