A Simple Insulated Thermometric Method for the Experimental Determination of Iron Losses

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***Abstract*- In this paper, we present a simple, versatile and cost-effective method for the experimental determination of the no-load iron losses in a PM machine. The proposed technique also enables obtaining the iron loss distribution in the machine. The latter is based on temperature rise measurements on specific locations of an electrical machine where thermal exchanges are minimized. The method principles are described as well as its implementation in a test bench. The method is used to measure the iron losses occurring in the stator of a Clawpole Transverse Flux Machine with Hybrid Stator with accurate results. The insulated thermometric method is finally used to compare the iron loss reduction offered by the use of two different stator core materials.**

I. Introduction

The energy conversion process of an electrical machine always implies losses. As the latter generate heat, they also determine the machine cooling requirements and efficiency. Therefore, a good knowledge of the losses dissipated in an electrical machine is usually required at the motor design stage.

The losses occurring in an electrical motor are usually divided between copper losses, iron losses and mechanical losses. They are generally either estimated or measured. Powerful numerical analysis tools or empirical formulas are now widely used by electrical machine designers for loss predictions. However, the latter become of limited value and measurements have to be done in certain cases: this is especially true at the machine design validation stage where accurate loss measurements on prototype motors are required.

The experimental determination of the iron losses can be an important step in a machine design procedure. It becomes crucial when it deals with the assessment of a new configuration especially designed to reduce the iron losses. This was the case for the Clawpole Transverse Flux Machine (CTFM) with hybrid stator [1] [2].

Transverse Flux Machines (TFM) are known for their excellent torque-to-mass and torque-to-volume ratios [3]. But this advantage is counterbalanced by some shortcomings such as high complexity, low power factor but also high iron losses [1-3]. The TFM shows a dependence of its force density upon its pole pitch [2]: as a consequence, the excellent torque capabilities of such machines are intimately linked with a high pole number. This generally leads to high electrical frequencies and thus to important iron losses, which often limit the machine rotational speeds to avoid cooling difficulties or to prevent a decrease of the efficiency.

The problem of iron losses is particularly acute in CTFMs. Because of 3D magnetic flux paths and an unusual magnetic circuit shape, CTFMs are usually built from Soft Magnetic Composites (SMC) [1][2][4]. Despite their isotropic properties, SMC still suffer from high specific iron losses: for example, the specific iron losses of SMC material Somaloy 550® are 8 W/kg (50 Hz/1T) whereas those of Fe-Si M19 0.35 mm-thick laminations are 1.3 W/kg (50 Hz/1T) [2].

A new configuration of TFM, the CTFM with hybrid stator was recently proposed, with the main goal of reducing the machine iron losses [1] [2] (Fig 1). The iron losses reduction is achieved by splitting the stator in two parts, stator C-core and feet, made from different materials in order to limit the use of SMC material. As the stator feet are made with SMC, the machine C-cores can be made from low-loss material as Fe-Si laminations or amorphous materials (Fig 2).

Recent work on this configuration has lead us to compare two different magnetic materials for the stator C-cores. The effect of the use of Fe-Si laminated or amorphous cores on the iron losses occurring in a CTFM had to be quantified experimentally. The distribution of losses occurring in the different parts of the CTFM stator also had to be known. Therefore, the need for a simple, accurate, versatile and cost-effective method for the experimental determination of iron losses pushed us to investigate several techniques. In this paper, we present an experimental method for the evaluation of no-load iron losses, based on a modified thermometric approach.

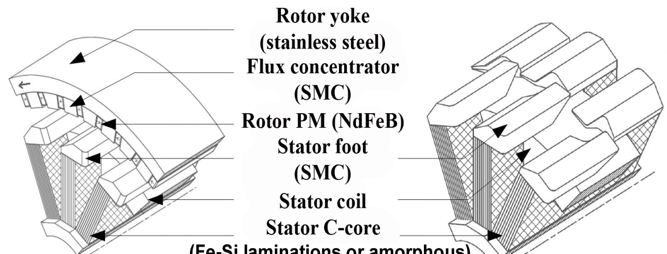

Fig 1: CTFM with hybrid stator (3 pole pairs of 1 phase) [1] [2].

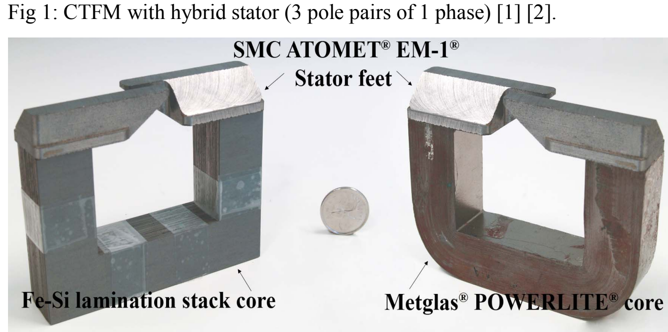

Fig 2: 2 CTFM stator poles with a Fe-Si core (left) and a Metglas® Powerlite® amorphous core (right) [1].

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II. Iron Losses Evaluation in Electrical Machines

Several methods of measuring the iron losses in an electric machine are to be found in the literature. Five of them are briefly discussed here before introducing the proposed insulated thermometric method.

A first method is the input power method. In the latter, iron losses are obtained by measuring, in different conditions, the input power fed into a prime mover driving the machine in which the losses are to be determined. As explained in [5], the iron losses can be deduced from 3 consecutive tests. The power fed to the prime mover is measured first coupled and then uncoupled from the test machine. Finally, the power input driving the test motor is once again measured with a dummy rotor to determine windage and friction losses. The machine total iron losses can then be calculated by subtracting the power measurements taken in the 3 tests. Although this method gives a direct measure of the losses, it can be sometimes inaccurate since the iron losses are obtained from a subtraction of similar quantities. As noted by Baholo *et al.* [6], a slight measurement inaccuracy can lead to a significant error in the iron loss measurement. Moreover, the more efficient a machine is, the less reliable are the results [7]. With this technique, it is also impossible to determine the spatial distribution of iron losses occurring in the motor.

A second method, the loss separation method, consists in using an equivalent electrical model to identify and segregate the losses occurring in an electrical machine. The model parameters are estimated experimentally with load and no-load tests. Losses are predicted using the different circuit parameters. If this technique has the advantage of relative simplicity, its accuracy also depends on the assumptions made in the machine model. Simplifications as sinusoidal currents and voltages, constant permeability of materials used or negligible harmonic fields and saturation phenomenon alter the method accuracy and applicability [7]. This technique neither gives the iron losses distribution.

A third method consists in evaluating the iron losses from empirical expressions. The losses occurring in a specific region of a motor, the stator teeth for example, can be determined from the flux density variation and using analytical iron loss expressions or manufacturer's data. However, iron losses predicted from manufacturer's curves often give underestimated predictions as noted in [5] and [7].

A fourth method for the determination of the iron losses is the calorimetric technique [6]. The latter is based on measuring the heat output (in joules) of a motor once it has reached thermal equilibrium. This method has the advantage to be accurate, as heat is a quantity that can be precisely measured. Despite its accuracy, the calorimetric method is also very cumbersome to apply. Fig 3 shows an overview of the system developed by Baholo *et al.* using this approach [6]. In this system, the no-load iron losses are evaluated from the temperature and flow rate of the air pushed in and out a closed insulated enclosure which contains the test motor connected to a prime mover (electrical motor). The complexity of this

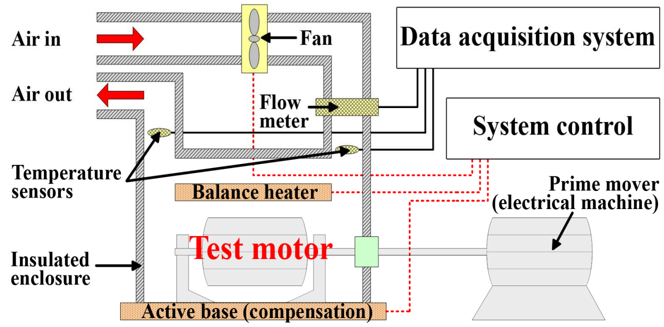

Fig 3: Example of calorimetric system developed by Baholo *et al.* in [6].

system resides in preventing heat losses, with compensating devices such as the heaters or the active base that can be seen in Fig 3. Another drawback of this method is the time it requires. Indeed, measurements have to be made once the test machine has reached a thermal equilibrium, which usually takes many hours. Finally, it is neither possible to predict the iron losses distribution in a machine with this technique.

A fifth method consists in obtaining the iron losses from the temperature decrease rate of a machine: this is the thermometric or temperature time method [7]. The latter is based on the principle that losses can be evaluated by measuring the temperature gradient at a point within the machine when the source of losses (i.e. excitation field) is removed. This method has the advantages of relative simplicity, is accurate and gives the iron loss distribution in a machine. The authors of [7] used this technique to evaluate the loss density distribution with good precision on various stator parts of a single phase induction machine. This last method appeared to be the most promising one as it satisfy most of our requirements.

The temperature time method described here relies on the fact that the source of losses can be removed. As the excitation field can be switched off in an induction machine as done in [7], it is unfortunately impossible to achieve in a PM machine. In a CTFM, the alternating flux flowing in the stator and produced by the rotor PM remanent field cannot be switched off instantaneously as it is not possible to stop the machine rotation instantly. The temperature time method described in this section is therefore not directly suitable for the iron losses determination in a PM machine. For this reason, we proposed a modified approach.

III. The Insulated Thermometric Technique

The thermometric method has been adapted to work with PM machines. The case of the CTFM with hybrid stator is considered here. The developed method consists in measuring the temperature rise on an insulated stator pole pair at the motor startup. In this section, the developed technique will be described as well as its implementation in a test bench.

Let us assume that a motor can be subdivided into homogeneous thermal blocks or regions with heat exchanges.

The iron losses occurring in a specific region of a motor are governed by the following heat balance equation:

$$P = \sum_{i=1}^{j} G_i \cdot (T - T_i) + C \cdot dT / dt \quad (1)$$

where P are the iron losses generated in the region where the measure takes place, G_i are the thermal conductances between the region and one of its j adjacent regions, C is the thermal capacity of the region concerned, T and T_i are respectively the concerned region and the adjacent regions temperatures. As a thermal steady state is achieved, (1) becomes:

$$P = \sum_{i=1}^{j} G_i \cdot (T_{steady\_state} - T_i) \quad (2)$$

with T_{steady_state} being the temperature of the region where the measure is taken in steady state.

A. Method description

From (1), one can calculate the iron losses occurring in a specific region of a machine, from its temperature rise and the knowledge of its thermal exchanges with surrounding regions. Unfortunately, the accurate identification and quantification of heat transfer mechanisms is not an easy task. The factors governing heat flow such as convection and radiation are quite difficult to determine numerically. The insulated thermometric technique proposed in this paper is based on the minimization of the heat transfer between adjacent parts.

Fig 4 shows the heat exchanges in a stator pole pair of a CTFM (see Fig 1 and Fig 2) when the motor is operated at no-load (PM excitation only and no current flowing in the stator windings). As depicted in Fig 4 by an electrical circuit representation, the iron losses occurring in the stator C-core are modeled by the current source P_C, as losses occurring in the feet are represented by the sources P_F. The C-core and feet possess thermal capacities respectively named C_C and C_F. Heat flows occurring between the C-core and feet are modeled by the resistance R_{CF}. Heat exchanges between the feet and the air are represented by R_{FA}. Finally, the heat flow between the C-core and its surrounding parts is modeled by the resistance R_{CA}.

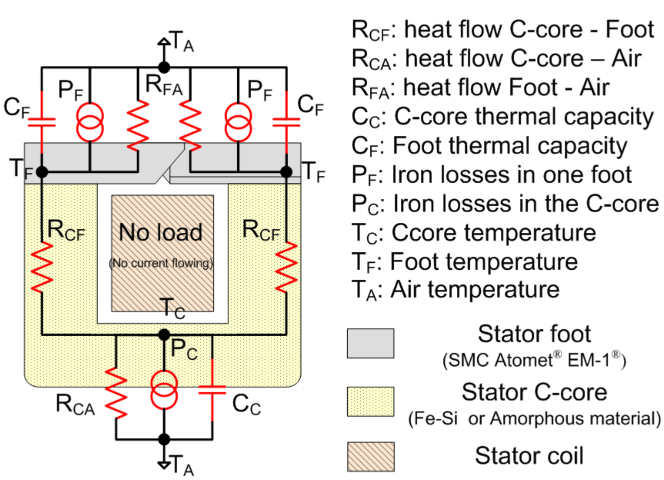

Fig 4: Heat transfers in a stator pole pair of a CTFM with no electrical load.

From (1), the components of the thermal circuit of Fig 4 can be expressed as follow:

$$\begin{aligned} 2 \cdot P_F + P_C &= 2 \cdot C_F \cdot dT_F / dt + C_C \cdot dT_C / dt \\ &+ 2 \cdot (T_F - T_A) / R_{FA} + 2 \cdot (T_C - T_A) / R_{CA} \end{aligned} \quad (3)$$

Under certain conditions, some of the heat exchanges depicted in Fig 4 can be neglected. First, one can neglect the heat dissipation between the stator feet and the air through the airgap (modeled by R_{FA} on Fig 4) at the motor startup (i.e. t →0), as $T_F - T_A$ is near zero. The heat transfer existing between the stator core and its surrounding parts (modeled by R_{CA} on Fig 4) cannot be neglected at the motor startup. R_{CA} is much smaller than R_{FA}, but it can be eliminated by thermally insulating the C-core from its adjacent parts. Under these particular conditions, (3) can be simplified as follow:

$$P_{stator} = 2 \cdot P_F + P_C \underset{t \to 0}{\approx} 2 \cdot C_F \cdot dT_F / dt + C_C \cdot dT_C / dt \quad (4)$$

Equation (4) shows that the total no-load stator iron losses occurring in one pole pair of a CTFM can be obtained from the temperature rises of the C-core and feet at the motor startup. However, the loss distribution between the C-core and feet cannot be directly calculated from (4). As the flux density distribution in the CTFM C-cores is rather homogeneous [1] [2], the C-core iron losses will be estimated from analytical expressions. The iron losses occurring in the stator feet can then be calculated by subtracting the estimated C-core losses to the total stator losses obtained from (4).

B. Method implementation

The insulated thermometric method was applied to the measurement of the no-load iron losses occurring in the CTFM stator depicted in Fig 1. Therefore, a test bench has been constructed to perform tests on a CTFM with either amorphous or Fe-Si cores. For simplicity and versatility, the CTFM is a one stator pole pair machine only. The realized test rig is depicted in Fig 5. In the test rig, a 15 pole pairs CTFM rotor is mechanically coupled to a DC motor. The prime mover enables iron loss measurements for CTFM flux frequencies going up to 400 Hz. A stator pole pair (C-core + feet) is inserted into the rotor with a thermally insulated fixation unit (Fig 6), as required by the method. As the rotor turns, the PM flux flows in the stator and the C-core and feet exhibit iron losses.

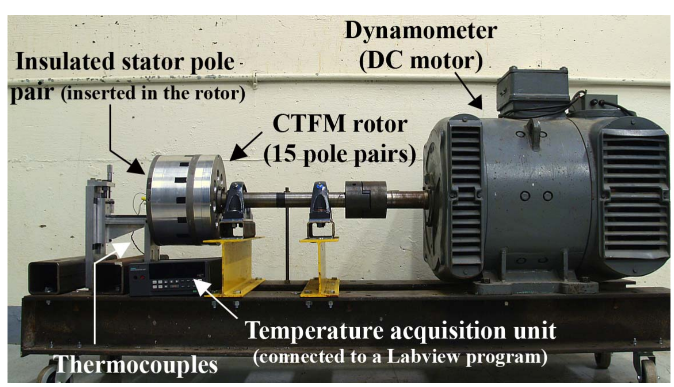

Fig 5: Test bench using the insulated thermometric method.

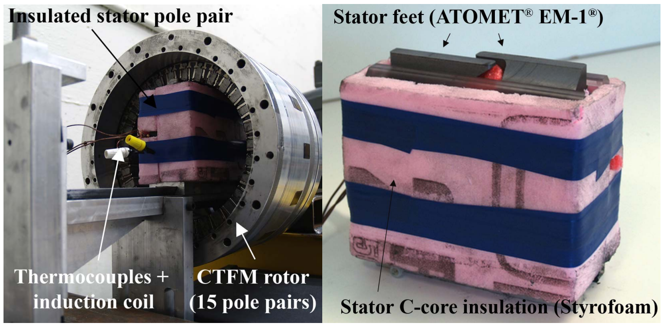

Fig 6: (Left): CTFM close-up. (Right) Stator C-core insulation system.

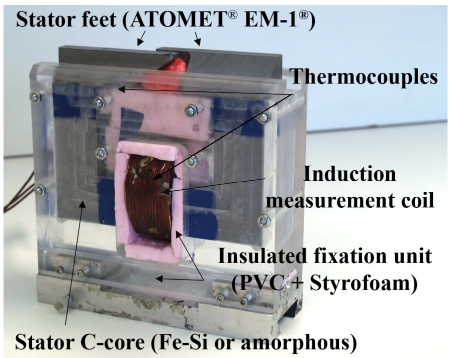

Fig 7: Insulated stator pole pair with its fixation unit.

The insulated fixation unit is made from PVC and Styrofoam®. The latter contains the stator amorphous or Fe-Si core (Fig 7). Thermocouples are placed on the core and feet in order to measure their temperature rise under PM flux excitation. Thermocouples were positioned as shown in Fig 7. One sensor was placed on the center side of the C-core, assuming there an equal contribution of each foot losses to the core temperature rise (2 values of R_{CF} being equal in Fig 4). Another sensor was placed on the foot bottom side, the latter part being assumed to be representative of the foot mean temperature. A coil is used to measure the core flux density. A temperature acquisition unit interfaced to a computer is used to record the C-core and feet temperature rises.

IV. Experimental Results

The test rig was used to perform iron loss measurements on one stator pole pair with Atomet® EM-1® SMC feet and a C-core made of either a Metglas® Powerlite® (AMCC 367S) amorphous core [8] or a M19 Fe-Si 0.35 mm thick lamination stack core (Fig 2). Tests were made for flux frequencies varying from 50 Hz to 400 Hz. The actual setup enables measuring the stator iron losses for stator core flux densities going up to 0.4 T. Higher core flux densities (> 0.4 T) could have been achieved by reducing the CTFM airgap. Unfortunately, the actual test rig could not provide airgaps below 2 mm. In future works, the test bench will be modified to achieve thinner airgaps and thus measurements at higher core flux densities. Nevertheless, the actual setup was suitable enough for our requirements.

For loss calculations, we considered thermal capacities of 450 J/kg°C for the SMC feet [9], 540 J/kg°C for the amorphous core [8] and 490 J/kg°C for the Fe-Si laminated core [10]. Masses of 0.129 kg for each SMC foot, 0.995 kg for the Fe-Si core and 0.825 kg for the amorphous core were also considered. Rewriting (4) with these values gives:

$$P_{stator\_M19} \underset{t\to 0}{\approx} 2\cdot 450\cdot 0.129\cdot dT_F/dt + 490\cdot 0.995\cdot dT_C/dt \quad (5)$$

$$P_{stator\_Powerlite} \underset{t\to 0}{\approx} 2\cdot 450\cdot 0.129\cdot dT_F/dt + 540\cdot 0.825\cdot dT_C/dt \quad (6)$$

where P_{stator_M19} and $P_{stator\_Powerlite}$ are respectively the losses measured in the stator pole pair with the Fe-Si laminated core and the amorphous core. This section shows experimental results obtained with the test rig. An example of iron losses calculation from temperature data is also presented, as well as the method used for the losses distribution determination.

A. *Example of temperature rise and loss measurements.*

Fig 8 shows an example of temperature rise measured on the foot and C-core of the stator pole pair made with the Fe-Si core (Fig 2 left). Fig 9 displays the same temperature rises taken in the case of the stator pole pair configuration with the amorphous core (Fig 2 right). Both tests were done for a PM flux frequency of 400 Hz and a core flux density of 0.36 T.

It can be observed on Fig 8 and Fig 9 that the C-core and foot reach a thermal steady state after 4 hours. In both experiments, one can also notice that the foot final temperature is higher than the C-core temperature. This observation let us suppose that the foot exhibits higher iron losses than the core.

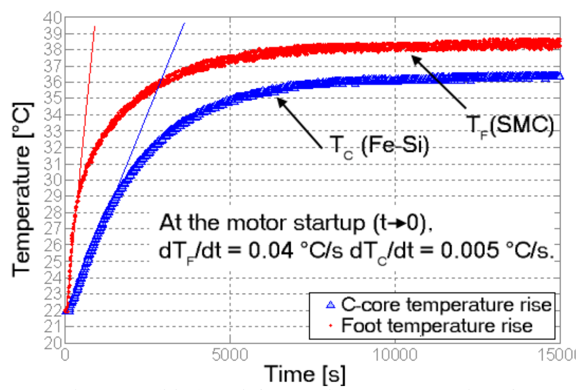

Fig 8: Fe-Si C-core (blue) and foot (red) temperature rises for a PM flux frequency of 400 Hz.

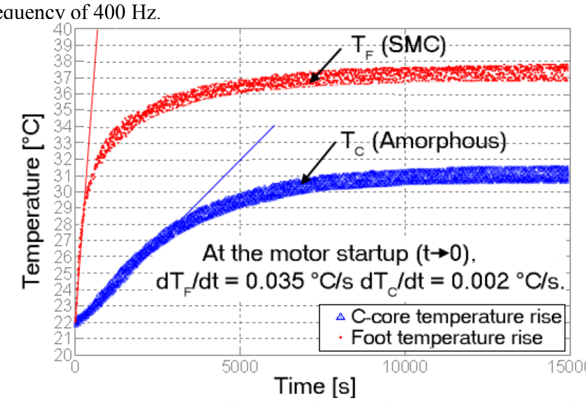

Fig 9: Amorphous C-core (blue) and foot (red) temperature rises for a PM flux frequency of 400 Hz.

Finally, the temperature rise of the amorphous core observed on Fig 9 is significantly lower than the temperature rise of the Fe-Si core shown on Fig 8: this let us expect lower iron losses in the stator pole pair with the amorphous core than in the configuration with the Fe-Si core.

From Fig 8, the slopes of the initial temperature rises of the Fe-Si C-core and foot are respectively found to be $5.3 \cdot 10^{-3}$ °C/s and $4.0 \cdot 10^{-2}$ °C/s. The slopes of the initial temperature rise of the amorphous C-core and foot are respectively estimated to $2.1 \cdot 10^{-3}$ °C/s and $3.48 \cdot 10^{-2}$ °C/s from Fig 9. From (5), the losses in the stator pole pair (core + feet) with the Fe-Si core are estimated to 7.23 W. From (6), the losses in the stator pole pair with the amorphous core are found to be 4.98 W. Calculations made from (5) and (6) confirm that the configuration with the amorphous core exhibits lower losses.

B. Evaluation of the iron losses distribution between the stator C-core and feet.

As said before, a direct estimation of the iron losses distribution between the C-core and feet cannot be obtained from (5) or (6). However, the latter was deduced from analytical expressions for the iron loss determination in the C-cores ((7) and (8)):

$$P_{M19} \underset{\substack{0.2\text{T}<B_{core}<0.5\text{T} \\ 50\text{Hz}<f<400\text{Hz}}}{=} m \cdot \left[0.0203 \cdot B_{core}^{1.716} \cdot f + 7.86 \cdot 10^{-5} \cdot B_{core}^{2} \cdot f^{2}\right] \quad (7)$$

$$P_{\text{Powerlite}} \underset{\substack{0.2\text{T}<B_{core}<0.5\text{T} \\ 50\text{Hz}<f<400\text{Hz}}}{=} m \cdot \left[0.008 \cdot B_{core}^{1.642} \cdot f + 3.50 \cdot 10^{-6} \cdot B_{core}^{2} \cdot f^{2}\right] \quad (8)$$

where P_{M19} and $P_{Powerlite}$ respectively represent the iron losses measured in the Fe-Si laminated core and amorphous core, m the core mass, B_{core} the core flux density and f the PM flux frequency. Equations (7) and (8) were cross-validated with independent iron loss measurements performed on Metglas® Powerlite® (AMCC 367S) amorphous and M19 Fe-Si 0.35 mm thick lamination stack cores for frequencies going from 50 Hz to 400 Hz and core flux densities going from 0.2 T to 0.5 T. The measurement protocol used is similar as the one described in [11]. The core flux density of a CTFM with hybrid stator is constant in the whole core as explained in [1] and [2]. The core flux density being measured in the test rig, (7) and (8) can be employed to evaluate the iron losses occurring in the C-cores. As explained in [1], it is not possible to use similar expressions to evaluate the iron losses in the SMC feet, the flux distribution in these SMC parts being too inhomogeneous. The feet losses can however be deduced from (5) to (8):

$$P_{SMC} = P_{stator\_M19} - P_{M19}\left(B_{core}, f\right) \quad \text{or} \quad (9)$$

$$P_{SMC} = P_{stator\_Powerlite} - P_{Powerlite}\left(B_{core}, f\right) \quad (10)$$

where P_{SMC} are the losses occurring in both feet, P_{stator_M19} and $P_{stator\_Powerlite}$ are respectively the iron losses in the Fe-Si and amorphous C-cores calculated from (5) and (6).

Let us take the example of the temperature rises depicted in Fig 8 and Fig 9. In this example, we consider the case where the C-core (Fe-Si and amorphous C-cores) flux density is measured at 0.36 T and the PM flux frequency at 400 Hz. In the configuration with the Fe-Si core, the iron losses occurring in the C-core are found to be 3.04 W from (7). Then, the iron losses in the feet are estimated to 4.20 W from (9). In the case of the stator pole pair with the amorphous core, iron losses occurring in the C-core are estimated to 0.60 W from (8). Finally, the feet iron losses of the configuration with the amorphous core are found to be 4.37 W from (10). The latter calculated values confirm the supposition made before, stating that the iron losses in the feet are more important that those in the C-core.

C. Comparison of the stator iron losses of a CTFM with amorphous core and with Fe-Si core using the insulated thermometric technique.

The insulated thermometric technique described in this paper has been used to compare the no-load iron losses occurring in the stator of a CTFM with either amorphous or Fe-Si core. Iron loss measurements for PM flux frequencies from 50 Hz to 400 Hz and for a core flux density of 0.36 T were performed according to the protocol described in section A (Fig 10). The method and test rig developed helped us to show experimentally a consequent iron losses reduction of up to 30 % of the total stator iron losses provided by the use of an amorphous stator core (Fig 10).

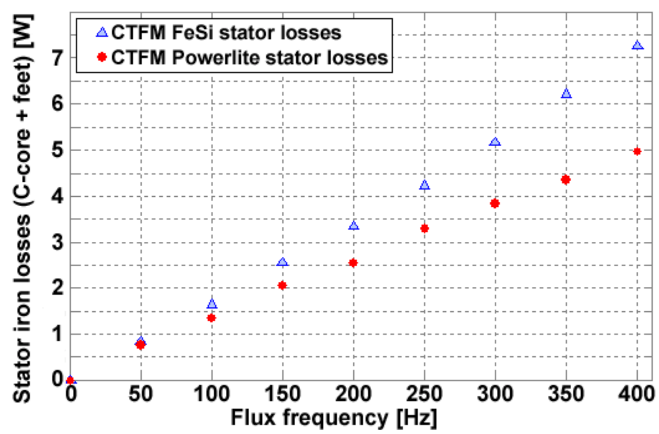

Fig 10: Experimental measurements of the stator iron losses in a one pole-pair CTFM with Fe-Si core (▲) / with a Metglas® Powerlite® am. core (●).

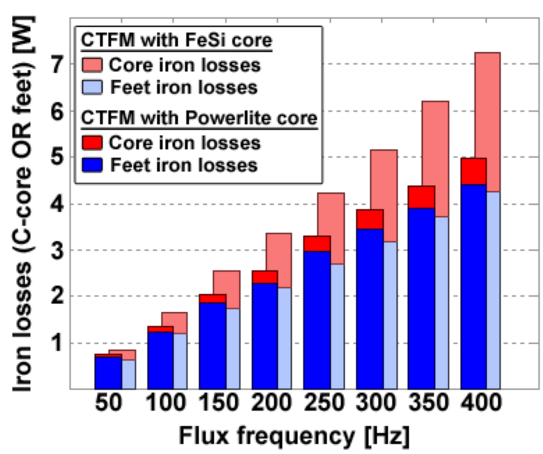

Fig 11: Stator iron losses distribution in the machine core and feet in the one pole-pair CTFM with Fe-Si core (light) / with a Metglas® Powerlite® amorphous core (dark). Bar height is the same in Fig 10.

Following the method described in section B, loss distributions between the C-core and feet were evaluated for each stator iron loss measurement taken (Fig 11). The stator loss segregation gets our attention to the important proportion of iron losses occurring in the feet: indeed, one can notice that the feet iron losses represent from 89 % to 91 % of the total losses in the CTFM with the amorphous core, whereas they constitute 59 % to 75 % of the total losses occurring in the CTFM with the Fe-Si core.

The experimental results presented in this section demonstrate the feasibility and show an example of application of the insulated thermometric method. Further works will be done to validate this technique. Comparisons with other methods or with finite element simulation results could be performed as validation. As both experiences were made in the same conditions (same frequencies and core flux densities), the losses occurring in the feet of the CTFM with the amorphous core and those of the CTFM with the Fe-Si core should be nearly the same. From the results shown on Fig 11, only slight differences can be noticed (10 % max) between the feet losses occurring in both tests. Although this observation does not constitute a validation itself, it indicates nevertheless that the method is accurate and reliable.

V. CONCLUSION

This paper presents a simple, versatile and cost-effective method for the experimental determination of the no-load iron losses in a PM machine. The insulated thermometric method relies on temperature rise measurements on specific locations of an electrical machine where thermal exchanges are minimized. The proposed technique also enables obtaining the iron loss distribution in the machine. The method principles and its implementation in a test bench have been detailed, applied to a CTFM. Although the case of the CTFM only has been considered in this paper, this method can be used in other PM machines after minor modifications.

The technique has been applied to determine the stator iron losses occurring in a CTFM with hybrid stator. Experimental results obtained were accurate and significant enough for the assessment of a new motor configuration especially designed for iron loss minimization: the CTFM with amorphous stator cores [1]. The experimental results obtained have shown that the method is accurate and reliable but further works will be devoted to cross-validate this technique by other methods.

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