International Journal of Energy and Power Engineering
2015; 4(5): 248-256
Published online September 8, 2015 (http://www.sciencepublishinggroup.com/j/ijepe)
doi: 10.11648/j.ijepe.20150405.12
ISSN: 2326-957X (Print); ISSN: 2326-960X (Online)

Methods of Temperature Measurement in Magnetic Components

Abakar Mahamat Tahir[1, 2], Amir Moungache[1, 3], Mahamat Barka[1], Jean-Jacques Rousseau[3], Dominique Ligot[2], Pascal Bevilacqua[2]

[1]Faculté Des Sciences Exactes Et Appliquées de l'Université De Ndjaména, Département De Technologie, Ndjaména, Tchad
[2]Laboratoire Ampère Insa-Lyon 20, Avenue Al. Einstein, Villeurbanne Cedex, France
[3]Laboratoire LT2C (ex DIOM 2), Rue Du Dr Paul Michelon, Etienne Cedex, France

Email address:

abakarmt@gmail.com (M. T. Abakar), amirmab@yahoo.fr (A. Moungache), mahamat.barka@gmail.com (M. Barka),
Jean.Jacques.Rousseau@univ-st-etienne.fr (J. J. Rousseau), Dominique.ligot@insa-lyon.fr (D. Ligot),
Pascal.BEVILACQUA@insa-lyon.fr (P. Bevilacqua)

To cite this article:

Abakar Mahamat Tahir, Amir Moungache, Mahamat Barka, Jean-Jacques Rousseau, Dominique Ligot, Pascal Bevilacqua. Methods of Temperature Measurement in Magnetic Components. *International Journal of Energy and Power Engineering*. Vol. 4, No. 5, 2015, pp. 248-256. doi: 10.11648/j.ijepe.20150405.12

Abstract: In this paper, we reveal the different temperatures recorded in selected magnetic components and, we show the methods of determination and measurement used. As magnetic components have characteristics that strongly depend on the level of local temperature, it is essential to take into consideration the temperature and its influence on the magnetic and electrical characteristics of the component. From the modeling objectives, we describe the constitution, the originality and the main functions of the device used to determine the temperature of the material, its winding, and connection. Finally the result of deepened tests will be presented, allowing to determining parameters of our model. Our work focuses on the development of thermal models capable of determining the working temperature of the chosen magnetic component at given points. It aims to help develop a methodology for designing thermal models of magnetic components; an approach that will be validated through a practical demonstration.

Keywords: Thermal Model, Temperature, Magnetic Component, Thermocouple, Coil, Magnetic Material

1. Introduction

In order to determine the elements of the model, to reject certain parameters or validate the model, it is essential to carry out the measurement of the temperature in different parts of the magnetic component used in power electronics, that's to say (i.e.) the temperatures of the magnetic material, the temperature in the coiling, and the temperature of the connection. The model should also accurately measure the losses occurring in the magnetic material and the windings. To avoid damaging the magnetic component under test, we chose an indirect measure of average temperatures obtained from a bench test. Particular attention has also been paid to the extent of losses to minimize sources of error. In the first part, we present the principles of measurement of temperature used. In the second part, we describe the apparatus used. We specify its constitution, its originality, and its main functions, and finally we assess the accuracy of measurements.

2. Measurement of Temperature

2.1. Assumptions

We first recall our assumptions about thermal modeling of magnetic components to justify the measurement principles used that lead to the measure of average temperature [1, 2, 3, and 10]. Temperatures are assumed to be uniform in the material and in the different windings. Thus, a component made up of a magnetic circuit and the two windings will be defined by three figures of temperatures. Thus, we have to measure the average temperature of these elements in the one hand and validate the model in the other. For the same reasons, it is essential to measure the ambient temperature and the temperature of the connection.

Since we seek to design a model that can predict the temperature with only a few degrees difference to the most, we need to have a means of characterization to measure the temperature with equal to or greater accuracy, under either static (set temperature) or transient conditions. In addition to this, the temperature measuring device will minimally disturb the functioning of the component to be characterized.

2.2. Temperature Measurement Method

Two solutions are possible

- A direct method with a probe, a thermocouple, an IR sensor or another temperature sensor is frequently used. [4, 5, 11]. The direct method is difficult to implement, however. In fact, the geometric dimensions of magnetic components are sometimes too short to accurately allow fixing certain types of probes. Furthermore, the direct method requires priming the device under test (DUT) and possibly modifying it (drilling a hole to insert a temperature probe).
- An Indirect measurement that allows determining the average temperature of the magnetic material and the different windings. This approach typically used for thermal measurements in power electronics is more convenient than the direct method, since it does not require any modification of the component [6, 7, and 8]. It is based on the measurement of a quantity whose value is a function of temperature such as the variation of the threshold voltage of a diode in relation with the temperature. As for the magnetic components, their saturation is representative of the temperature of the magnetic material. In addition to that, the resistance of the coil reliably reflects the average temperature of the copper. We have chosen this approach since it has many advantages.

2.3. Measuring the Temperature of the Magnetic Material

Determining the average temperature of the magnetic material is the same as measuring the saturation induction. Indeed, as shown in Figure 1, the saturation magnetization is a function of temperature. This feature naturally depends on the type of material under study.

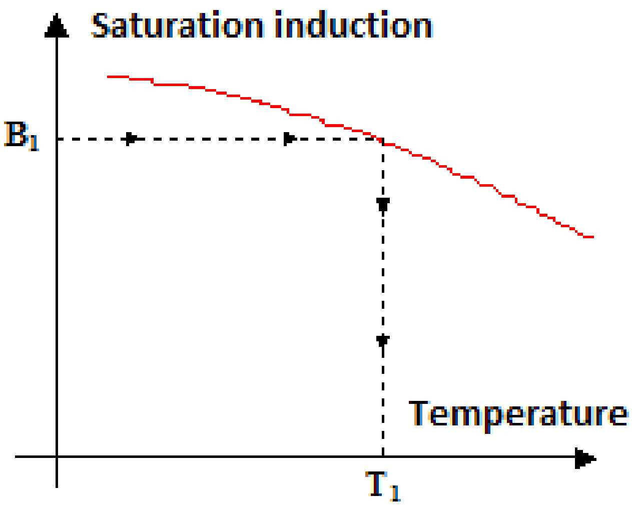


Figure 1. *Features of saturation inductionBsat = f (T) of a material.*

A first phase of identification is needed. It is to measure the saturation induction (saturation induction or induction for a given value of the applied field) for some values of the temperature. Typically a few points are sufficient between 20 °C and 120 °C due to the appearance of this feature. This characterization is to be performed once for a given material. There is a correlation between measuring the average temperature of the magnetic material and measuring the saturation induction using a flux meter. Measuring the saturation average is a non-destructive approach, simple to implement, and requires no instrumentation of the device under test since it has two coils.

2.4. Measuring the Temperature of the Resistance of the Winding

With the same approach, the average temperature of a coil is given by measuring the continuous winding resistance as shown in Figure 2.

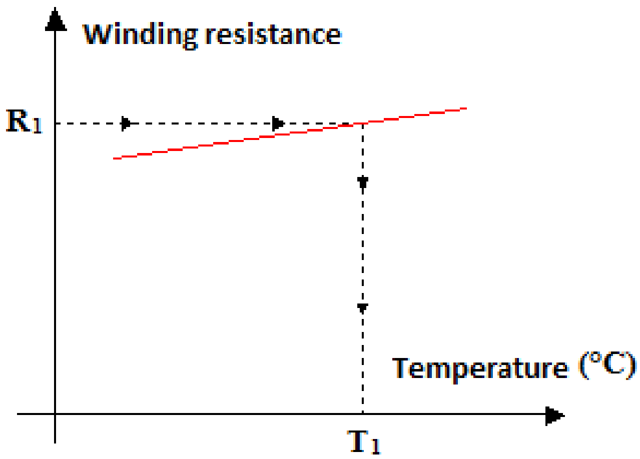


Figure 2. *Evolution of the resistance of a winding according to the temperature.*

The variation of a winding resistance versus temperature is given by: $R = R_0(1 + \alpha T)$ where R_0 is the resistance at 0°C and T the temperature. This variation is linear. The copper resistance approximately varies up to 30% when the temperature varies between 20°C and 125°C which requires an accurate measurement process of the winding resistance. This method with 4 connection wires provides satisfactory results with minimal complexity. For accuracy purposes it is better to proceed with the statement of the characteristic $R_{(Temperature)}$ of the pure copper rather than using α, the coefficient of the temperature.

2.5. Measuring the Temperature of the Connecting Terminals

We have shown in the previous section that the terminals of the magnetic component played an important role in the transfer of heat from the component outward. Typically, the coil is soldered to a printed circuit board, which is a much more effective heat sink as the tracks are wide. The temperature of the connecting terminals is not equal to the ambient temperature and the identification of the model parameters requires measuring this temperature. As an indirect measurement proves difficult, using a thermocouple is a solution that seems simple to be implemented. However, the validity and accuracy of the measurement are to be watched closely. Make sure that the thermocouple does not affect the heat transfer. Measures with the thermocouple seem to be complicated. Thus the following precautions are taken in order to not disturb the measurement accuracy. Thermocouples are considered to be accurate within ± 1 °C but great precautions are needed [9,10].

- They may pick up electrical noise
- They need to be calibrated to a “cold junction”.
- Their attachment to the DUT can be complicated.
- The wires of the thermocouple or disc type thermocouples may make the device to be measured considerably colder
- The wires of the thermocouples may obstruct or disturb the airstream.

3. Equipment Characterization

3.1. Incorporation

The thermal characterization of a magnetic component is to operate in conditions as close as possible to the nominal operation conditions (same constraints: current, voltage, frequency...) and periodically meet different temperatures. Temperature measurements should not disturb the trial or alter the magnetic component. The measurement time should be very short compared to the thermal time constants of the component (a few tenths of a second for all measures) [2, 4]. The following diagram (Figure 3) specifies the constitution of the panel that includes the following four subsets:

- A power supply that allows exciting the sample under test with the conventional forms of wave power electronics or by using a quasi - sinusoidal source;
- A device for measuring the saturation induction flow meter consisting of an integrator;
- A magnetizing device which allows access to the temperature of the magnetic material.
- Measuring device 4 for measuring the resistance of the windings and determine the operating temperature (or more).

3.2. A Switch Card

The equipment completed by a system for measuring the temperature of the connection consists of a thermocouple and an associated packer. This delivers 0 - 10V signal to the capture card.

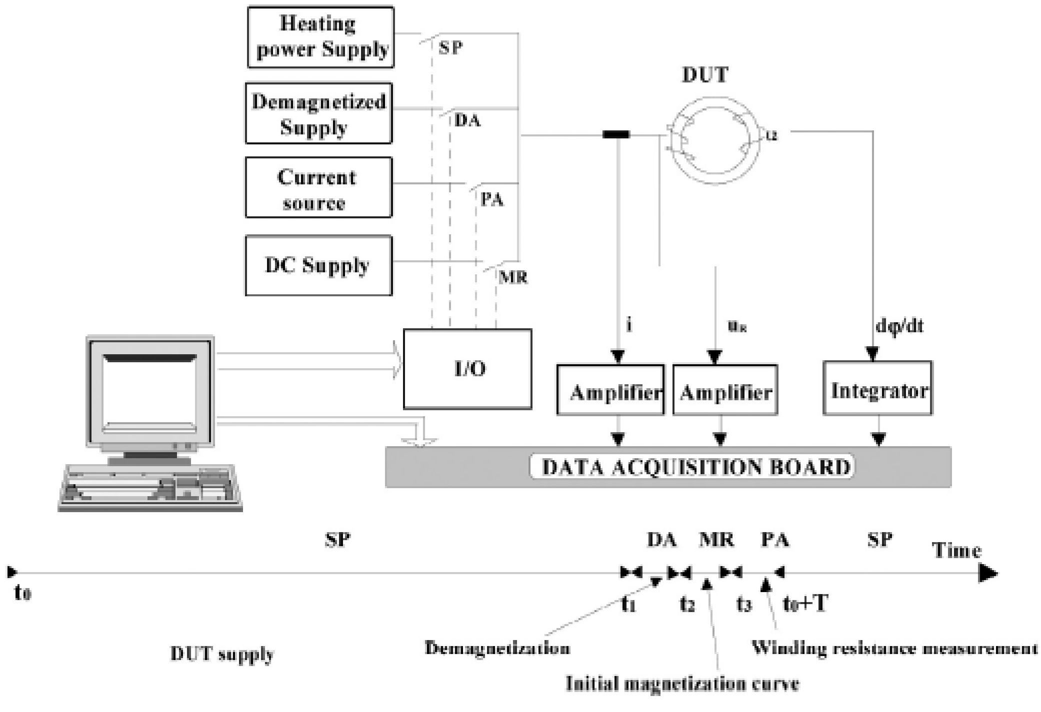


Figure 3. *Schematic diagram thermal equipment and operating timing.*

At regular intervals (for example every minute), the temperature measurement is carried out in the following order:

- Disconnection of the power source.
- Measuring of the average temperature of the magnetic material which involves the demagnetization of the material.
- The connection of the excitation source and recording of the initial magnetization curve from magnetization to saturation.
- Measuring of the average winding temperature by commissioning a DC current source, and measuring the resistance of the winding. This process is repeated if necessary for different windings.

- The unit is controlled by a computer with a capture card for analog quantities measures and a map of digital inputs/outputs for the control of different elements. It also enables the processing and data storage.

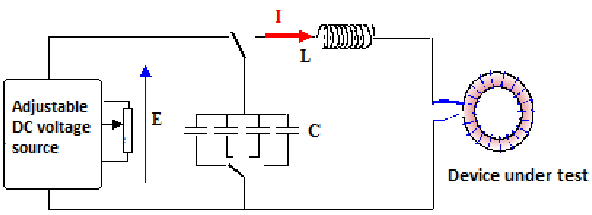
3.3. The Power Source

It is typically composed of a switching power supply that provides power to the sample under test by the usual wave electronic forms of power. For accuracy purposes mentioned above, this power source can also be replaced by a sinusoidal voltage source or a DC power supply based on the tests to be performed and the expected extent of the losses dissipated in the component accuracy. The start and stop of this source in all cases are controlled by the PC via inputs / outputs digital card.

3.4. The Device for Measuring the Saturation Induction

It comprises a demagnetization circuit and a flow meter integrator:

The demagnetizing circuit: The demagnetization is obtained using an oscillating capacitor discharge through the coil. This is controlled by the PC via the digital input output card assembly mainly composed of an LC circuit. The capacitor is charged at constant voltage of adjustable amplitude, a potentiometer is used to control the charging voltage E of the capacitor, which adjusts the amplitude of max ($I_M = E\sqrt{\frac{C}{L}}$).The oscillating frequency of the discharge is adjusted by a set of capacitors (C_1 and between 22 uF). A switch allows you to choose different values of the capacitor C to adjust the frequency of the oscillating discharge ($f = \frac{1}{2.\pi.\sqrt{LC}}$).



C ranging from 1 µF to 22 µF and $L \approx 100mH$ source voltage 0 -150V

Figure 4. *Circuit demagnetization.*

3.5. The Fluxmeter

Recording the characteristic ϕ(i) and B(H) is obtained by the simultaneous acquisition of the current in the primary winding and the integral of the induced electromotive force (emf) across the terminals of an auxiliary winding (the emfis proportional to the derivative of the flux $e_2 = -n_2 \frac{d\varphi}{dt}$). The knowledge of the characteristics of the test sample (effective area A_e, the effective length, number of turns of winding exciter winding n_1 and n_2 measurement) ϕ(i) or B (H) provides the magnetic characteristics) from the measurements. The magnetic field is given by the equation: $H(t) = \frac{n_1.i_1(t)}{l_e}$. The flow is obtained by the integration of the analog voltage output as knowing of the numbers by coil $\varphi(t) = -\int \frac{e_2(t)}{n_2} dt$. The flux meter is equipped with programmable integrator whose time constants are chosen so that to give output signals whose amplitude is as close as possible to the full scale. The average induction is obtained from: $B(t) = \frac{\varphi(t)}{Ae}$

Figure 5 below describes the constitution of the flow meter integrator including the devices shown below:

- A demagnetization;
- An excitation circuit comprising a function generator driven by the PC and a power amplifier;
- A flow measurement performed by a programmable integrator;
- An exciter current measurement I_1 photo current ~~is~~ obtained by means of a non-inductive shunt.

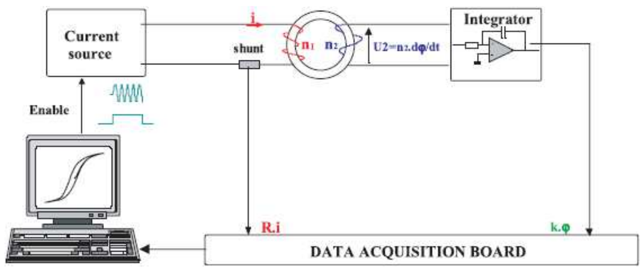


Figure 5. *Integratorfluxmeter.*

Grabber card Keithley DAS 1802 Keithley inputs and outputs PIO12
Wavetek Model 184 generator triggered - Amplifier Sodilec 36V- 12A

The material is demagnetized before processing the measurement, (Figure 6). Next, a measurement is performed without injecting current (I(t) = 0) in the exciter coil which can take into account the drift of the analog integrator. Finally, we proceed to the statement of the initial magnetization curve. To overcome the problems of the drift, the results of the first acquisition at zero current is subtracted from those of the second measurement.

Measuring time (demagnetization - measurement drift and measurement signal: 0.2s).

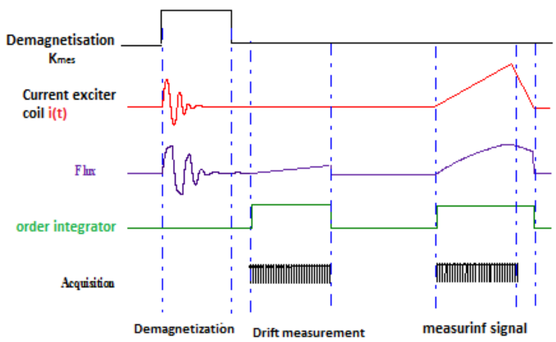


Figure 6. *Sequencing steps to the statement of the initial magnetization curve.*

Figure 7 below shows the results of measurements made using the flow meter integrator.

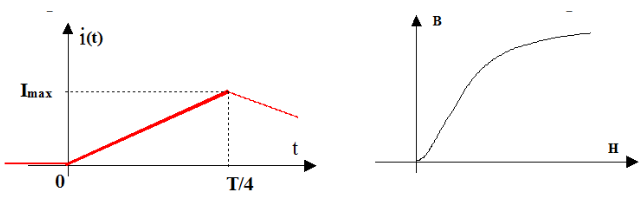


Figure 7. *First magnetization curve.*

3.6. Apparatus for Measuring the Resistance of the Winding

Determine the average winding temperature that can be achieved in another way by measuring the DC resistance of the coil floor by four voltmetersto access the value of the resistance method with sufficient accuracy.A source of energy injects a continuous current in the winding to determine the strength;and four valuesare available (0.5 - 1 - 2.5 and 5A).

Two programmable instrumentationsamplifiers are used: one for measuring the current (voltage across a shunt), the other for measuring the voltage across the winding enables operation in full-scale (0 -10V).

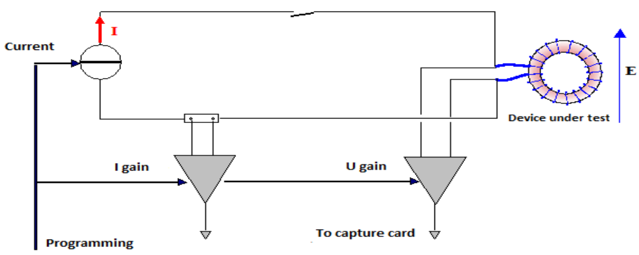


Figure 8. *Apparatus for measuring the resistance of the coil.*

3.7. Switch Card

A switch card can be connected sequentially to the sample under test with the followingdifferent subsets of the bench characterization: power supply, circuit demagnetization, flow meter integrator device for measuring the resistance of the winding.

To control the various elements (demagnetization heating, etc.), 8 logical signal generators are managed using 8 relays. This card is controlled from a digital input -output card (PIOcard).

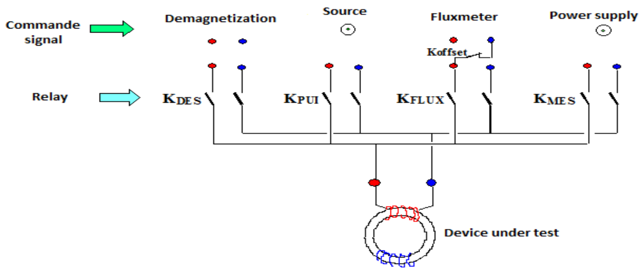


Figure 9. *Simplified Block Diagram of the switch board.*

This card allows you to connect the magnetic component under test that is electrically isolated, and delivers control signals to it. The typical measurement cycle is indicated in Figure 10 below:

From t_0 to t_1 (relay closed K_{PUI}), the component under test is powered by the power source, the duration of this first phase covers about 99 % of the period T. As the component works in conditions very close to its nominal operating conditions, the temperature will rise.

At time t_1,the phase demagnetization of the material (relay closed K_{DES})starts.

From t_2 to t_3, there is the first magnetization characteristic to derive the average temperature of the magnetic material (K_{FLUX} closed relay).

From t_3 (K_{MES} relay closed),the resistance of the winding is measured, thus determining the temperature of the coilat time t_0 + T (K_{PUI} relay closed).Then, a new measurement cyclestarts.

With heating for 60s (for example), we have about 800 ms for measurements (demagnetization, first magnetization, and resistance measurement).

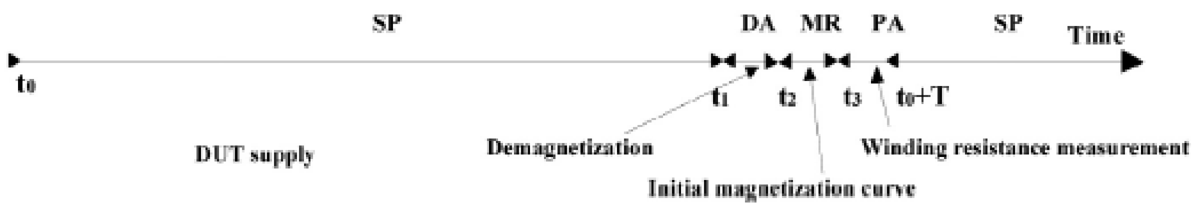


Figure 10. *Measuring cycle.*

Conventionally, several tens of points of measurement are indicated.The length between two points is greater than a minute while the time required for measures does not exceed a few tenths of a second. Of course, it is all about sizes that depend mainly on the thermal time constants of the studied component.

All control signals are provided by the PC, and the switch board ensures the format and the galvanic isolation.

3.8. Software Test Drive

The software for the control of the tester was developed using the software called test point. This software is to develop and uses test programs, measurement, and data acquisition. All acquisitions are managed via a PC with an analog card and a digital map. This program also allows the measurement acquisition, processing and display, and data storage. Various parameters for the test are provided by the operator, these steps include:

- The choice of parameters running the test (number of points of measurement, frequency...);
- The parameters for the acquisition of the initial magnetization curve (time constant of the integrator, sampling frequency, the value of shunt used for current measurement, the sample data: number of turns of the windings, section and effective length);
- The semi -automatic determination of the gain of the instrumentation amplifier according to the current selected for measuring the winding resistance (manual selection of current 0.5,1.25, 2.5 and 5A);
- Then the acquisition proceeds automatically until the full display of curves giving the evolution of different temperatures as a function of time.

4. Validation of Measuring Bench

Various tests were carried out in order to validate the measurements obtained using the device described above. We were particularly interested in:

- Checking that the measurement (relevant to the sampling time) did not affect the heating of the component under test.
- Analyzing the validity of the temperature measurement using the connection of a thermocouple.
- studying the repeatability and the accuracy of the measurements of the average temperatures of the winding and the magnetic material.

4.1. Influence Measures on the Heating of the Component Under Test

Any measurement device would typically modify the circuit in which it takes place. In these circumstances, it is important that the perturbation induced by the device should be negligible. This notice applies to any measurement process and naturally so to measuring temperatures. This is why it was essential to ensure that the average temperature measuring of the winding and the magnetic material had a negligible impact on the heating of the component under test. Sampling the temperature every minute with 800ms holding time unlikely leads to significant disturbances. For this reason, it was necessary to check.

We carried out several types of tests to check the validity of this approach: for an 800ms holding time, the device under test is not supplied. Then it is excited by different sources for performing the measurements. To ensure that the absence of power during the measurement does not significantly disrupt the heating of the component, we observed the evolution of temperatures by varying the sampling time. The figures below show the results for two tests, one corresponding to one minute and the otherto five minutes as sampling times.

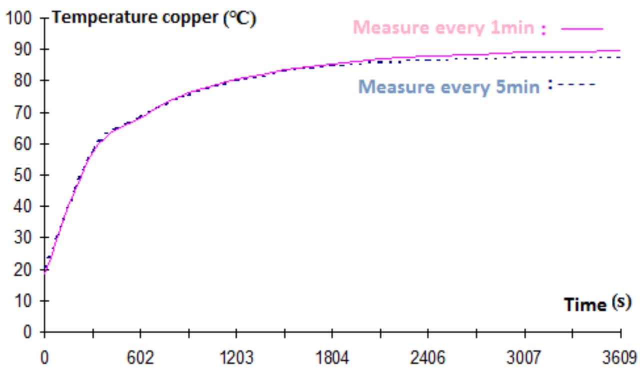


Figure 11. *Influence of the sampling time of the copper temperature.*

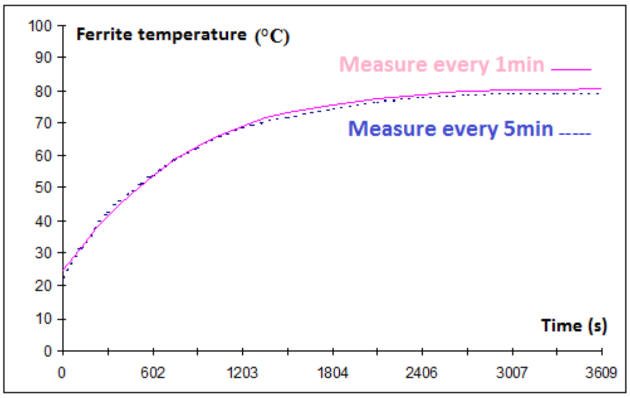


Figure 12. *Influence of the sampling time of the ferrite temperature.*

The tests do not show significant temperature differences between copper and ferrite. The maximum gap between their temperatures reached only 2 (two) degrees. Therefore, it can be concluded that for a sufficiently long holding time (more than 1 minute) the influence of the measurement process is negligible.

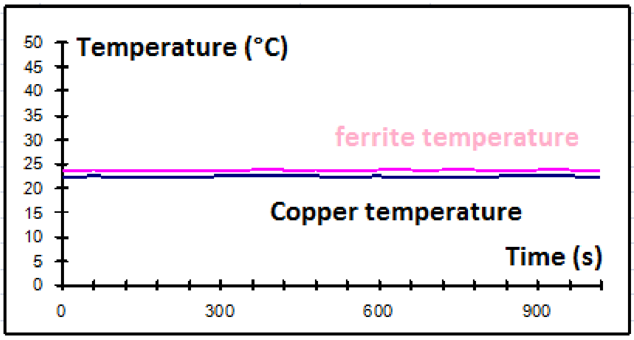


Figure 13. *Influence of the measurement of the temperature of the component under test (Ferrite temperatureand copper temperature).*

We also verified that the measure doesn't lead to additional heating of the component under test, neither heating due to the current demagnetization, nor excitement due to the measurement of the winding resistance. For this reason, every single minute, we recorded the unchanged temperature of every component in the category. Figure 14 below shows a high temperature stability of the tested component. The measured temperature of the copper fluctuates between 22.3 °C and 22.6 °C while that of the ferrite varies between 23.5 and 23.9 °C. As assessed above, this confirms that the temperature of the component under test doesn't change significantly when it is sampled every minute.

4.2. Temperature Measuring Means for Connection to a Thermocouple

Measuring the temperature of the connection using a thermocouple is a major challenge. Many tests have been made to obtain, first a reproducible measurement, and then a measurement as close as possible to reality.

The reproducibility of the measurement depends mainly on how the thermocouple is linked to the connection. Figure 16 below shows what seems the most appropriate way to do it. The tip of the thermocouple is covered with a drop of tin. It is not just the welding thatis important. Particular care should be taken of the position of the thermocouple. The use of a magnifying glass helps to position the tip of the thermocouple as near as possible to the conductor in order to ensure a good replication of the measurement.

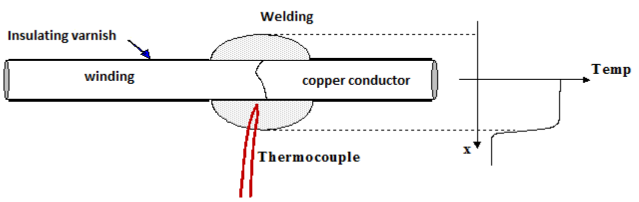


Figure 14. *Measurement of the temperature in connection with a thermocouple.*

In order to assess the accuracy of the measurements, we compared the results of thermocouple measurement with those obtained by an indirect method. The system is described in Figure 15below. A coil of about 30 turns is driven by a direct current I, whose intensity is adjusted to achieve a significant heating (up to 120 °C). The winding temperature was measured:

- Straightforwardly bythethermocouple placed in the center;
- Indirectly by measuring the resistance of a part of the winding.

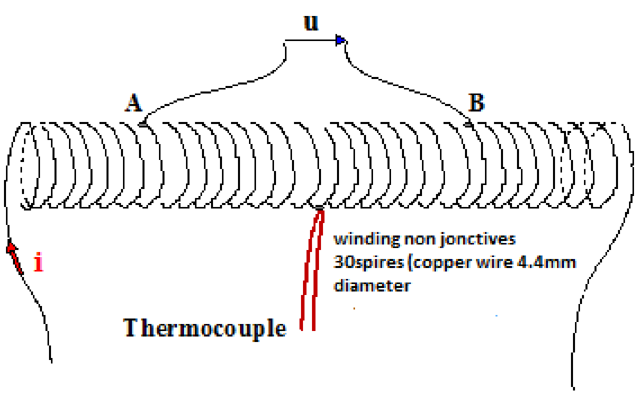


Figure 15. *A comparison between the direct measurement and the indirect measurement of the winding temperature.*

Given the geometric dimensions, it is reasonable to consider that the coil has a uniform temperature between the two measuring points A and B. Thus, the comparison of both measurements is legitimate.

Figure 16 below is entirely representative of the many comparisons made. We canobserve that the temperature indicated by the thermocouple is about 10% lower than the one obtained by the indirect method.

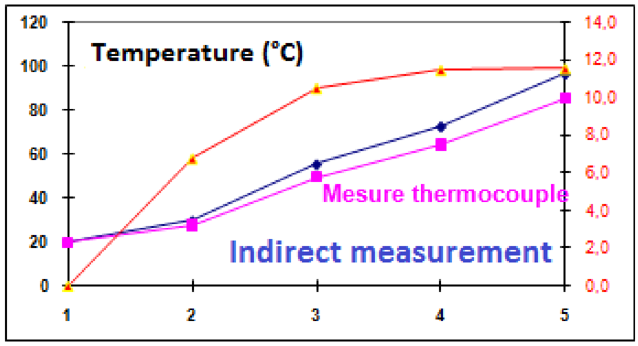


Figure 16. *Comparison of direct measurement and indirect measurement.*

It is difficult to explain this difference. Several hypotheses are plausible:

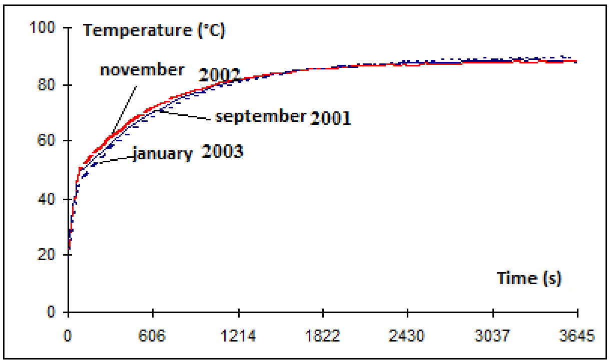
- the thermocouple acts as a thermal shunt. This contributes to locally reduce the temperature of the connection;
- as the thermocouple is not centrally located, it does not measure the temperature of the copper, but a slightly lower temperature taking into account the temperature gradient between the center of the copper and the ambient air;
- The thermocouple is not solidly welded (rather it is a cold junction).A thin layer of air surrounding the active part helps to locally reduce the temperature measured very locally.

Our aim was to improve measurement accuracy but the many trials carried out did not provide results with better than 10% accuracy. This type of precision will only be found in the determination of the elements of an equivalent circuit.

Precision and reproducibility of the measurement temperature of the winding and the magnetic material.

To characterize the reproducibility of measurements achieved through the use of the heat bench, we carried out the same test over three years. This test (DC_{test}) consists in feeding the sample under test by a high magnitude direct current to raise the temperature changes of the copper and the ferrite over a given time. Figure 20 below corresponding to the results obtained during the last three years shows good replication of the measurements.

Regarding the accuracy of measurements, we placed in a thermal temperature controlled enclosure, the sample previously characterized. For three different temperatures (62 °C, 91 °C and 120 °C)programmed into the heating chamber, we set a direct measurement for the internal temperature, and an in direct measurement for both the winding temperature and the temperature of the magnetic material. These measurements were carried out in steady state which allowed the temperature of the component to be uniform. About thirty measures were carried out each time.



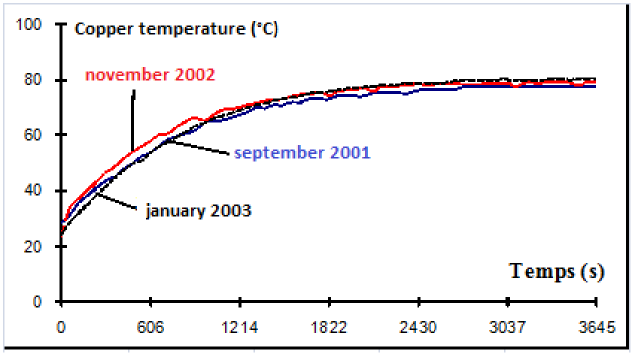


Figure 17. *Measurement repeatability.*

Figures 17, 18 and 19 indicate the temperature distribution of the copper and that of the magnetic material measured by the indirect method previously described

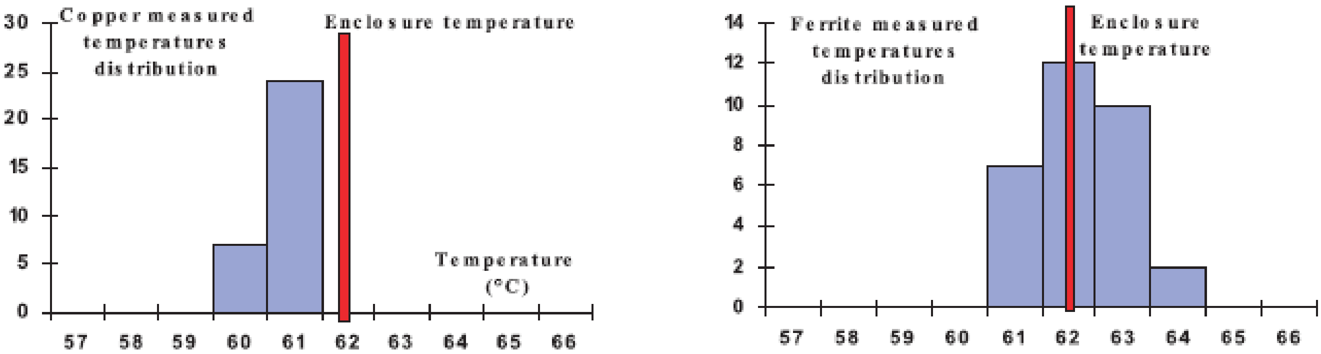


Figure 18. *Measured temperatures distribution at* $T_{Enclosure}$ *= 62 °C.*

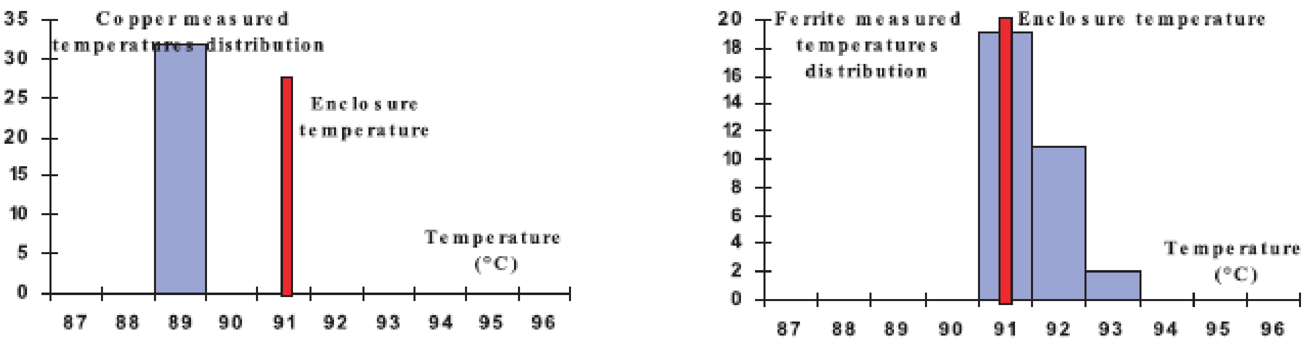


Figure 19. *Measured temperatures distribution at* $T_{Enclosure}$ *= 91 °C.*

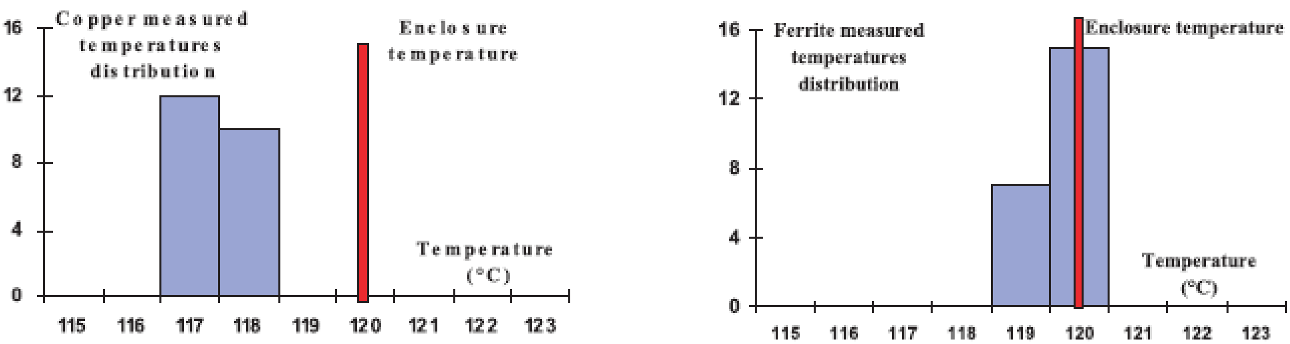


Figure 20. *Measured temperatures Distribution at* $T_{Enclosure}$ *= 120 °C.*

The above figures show that the accuracy of the measurement effected is very acceptable, as the variation is only about ±2°C. Only the winding temperature in the higher temperature conditions is stained by a larger error of about±3°C.

5. Conclusion

In order to measure the temperature of the component under test, a vital step into the determination of the elements of the models, we developed a thermal characterization bench. To avoid the modification of the components, we mainly adopted the indirect measuring method. It consists in determining the temperature of the winding and that of the magnetic material from measurements of resistance and initial magnetization curve. Only, the determination of the temperature of connection requires a direct thermocouple measurement. For each of these methods we verified the validity of the approach and the accuracy of the results. So we can state and support that we have set up an appropriate bench for the thermal characterization of magnetic components in permanent or transient states. This bench was also used to validate several proposed models.

The quality of a model depends largely on the accuracy of losses and temperature measurements. We have developed a methodology to accurately determine the various losses in a magnetic component in a frequency range extending from DC to maximum operating frequency in several hundred kHz. Accuracy of measurement had been a constant concern in our approach.

References

[1] Abakar M. T. Modélisation thermique des composants magnétiques utilisés en électronique de puissance. Thèse de Doctorat, INSA de Lyon, 2003, 114 p.

[2] Abakar M. T., J.J ROUSSEAU, BEVILACQUA P., and MAHMOUD Y.Thermal measurementequipment for magnetic component.Eur.Phys.J.appl.Phys, 2005, 30: 57-64.

[3] Abakar M. T. et al. Measuring methods of losses in magnetic component. Pelagia Research Library. Advances in Applied Science Research, 2014, 5(1):156-168.

[4] M. T Abakar et al. Magnetic components Thermal modeling. Part 1: Theorical Issues. IREMOS ISSN 1974 - 9821 Vol 2 N°1 Fev 2009.

[5] Choi B., PEARCE J. A., WELCH A. J. Modeling infrared temperature measurements: comparaison of experimental results with simulation. Conference title: Laser-Tissue Interaction XI: Photochemical, photo thermal and photomechanical, San Diego CA, USA, 2000, 3914: 48 - 53.

[6] Rousseauj. J. Modélisation des composants magnétiques. Habilitation à Diriger des Recherches. INSA de Lyon, 1996, 104 p.

[7] Joiner B., Adams V. Measurement and simulation of junction to board thermal resistance and its application in thermal modeling. Annual IEEE Semiconductor Thermal Measurement and Management Symposium, San Diego CA, USA, 1999, p 212-220.

[8] Thottuvelil V. J., WILSON T. G., OWEN H. A. High-frequency measurement techniques for magnetic cores. IEEE PESC 1985, p. 412-425.

[9] Imre. T. G., CRONJE W. A., VAN WYK. J. D., FERREIRA J. A. Loss Modeling and Thermal Measurement in Planar Inductors - A Case Study. IEEE Transactions on Industry Applications, November/December 2002, 38 (6): 634 – 647.

[10] *Petersson, A.* (Ericsson), *Conway, P.* (Murata Power Solutions) and *Boylan, J.* (TDK Innoveta). Thermal Measurements of Power Converters – How and Why? EPSMA. P14. 2009.

[11] Alaa, H. Magnetic components modeling including thermal effects for DC-DC converters virtual prototyping. Electric power. University Claude Bernard - Lyon I, 2014; p26-43.