NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE THERMAL BEHAVIOR OF DRY-TYPE TRANSFORMER SUPPLYING NONLINEAR LOADS

Mafra, R. G., Anselmo B.C.S, Belchior, F. N. and Lima e Silva S. M.M.
Heat Transfer Laboratory – LabTC,
Mechanical Engineering Institute - IEM,
Federal University of Itajubá - UNIFEI,
Av. BPS, 1303
Itajubá, MG, Brazil
E-mail: mafra534@gmail.com, brunocsa@gmail.com, fnbelchior@gmail.com, metrevel@unifei.edu.br

ABSTRACT

Thermal behavior of the transformers is affected by distorted loads caused by the influence of electronic equipment in the electric current. The aim of this work is to analyze the thermal behavior of a 5 kVA dry-type transformer working with linear and non-linear loads. Thermocouples and PT100 were used to measure the temperatures inside the cores. In addition, fans were used inside the transformers to analyze the influence of forced convection in the temperatures. Empirical correlations from literature were used to determine the average heat transfer coefficient used in the numerical analysis and to validate the results obtained in this work. The emissivity of the core surface was measured with a thermal camera. COMSOL software was used for the numerical simulation of the heating of transformers under the effect of certain loading and cooling conditions. Comparisons between experimental and numerical temperatures were carried out to validate the methodology. Hot Spots temperatures and their locations were also possible to be estimated with this methodology. The Hot Spots temperature in the core reached 20 °C above the transformer insulation limit. These temperatures and locations will serve in the future to optimize cooling projects of shell-type transformers.

INTRODUCTION

A few decades ago, the quality of electrical energy was not the focus of attention as it is today since the robust equipment that was used at that time was well tolerant of disturbances in the power supply. Today, with the advancement of power electronics, the nature of the loads has changed, and electrical equipment has become more sensitive to fluctuations in the quality of the power supplied [1]. Transformers supplied by sinusoidal voltages, when feeding non-linear loads, have their windings loaded by distorted currents, and, thus, there is an increase of electrical losses related to the non-sinusoidal condition [2]. As the internal losses increase, there will be a rise in the temperature of the transformer, implying a drastic reduction of its useful life. Within this context, it is possible to analyze the reduction of the useful life and variations in the thermal behavior of the transformer when submitted to different forms of load. From the analysis of temperature distribution for each type of load (linear and non-linear load), and by assuming room temperature as constant, it is possible to estimate the new electric losses for each situation. Including the highest temperature points (Hot Spots) [3].

NOMENCLATURE

A	[m²]	Core surface area
Cp	[J/Kgk]	Specific heat
g	[m/s²]	Gravity
Gr		Grashof number
h	[W/m²K]	Average heat transfer coefficient by natural convection
h_c	[W/m²K]	Average heat transfer coefficient by natural convection on the side surface of the windings
h_f	[W/m²K]	Average heat transfer coefficient by natural convection on the top surface of the windings
h_i	[W/m²K]	Average heat transfer coefficient by natural convection on the silicon iron bottom surface
h_l	[W/m²K]	Average heat transfer coefficient by natural convection on silicon iron side surface
k	[W/mK]	Thermal conductivity of the air
L_c	[m]	Characteristic length of the core by natural convection [m]
L_f	[m]	Characteristic length of the core by forced convection [m]
Nu		Nusselt number
Nu_c		Nusselt number for the side surface of the windings
Nu_i		Nusselt number for silicon iron bottom surface
Nu_l		Nusselt number for silicon iron side surface
Pr		Prandtl number
r	[m]	Winding radius
Ra		Rayleigh number
Re		
t	[s]	Time
T	[°C]	Temperature
$T2$	[°C]	Core 1 temperature
$T3$	[°C]	Core 2 temperature
$T4$	[°C]	Core 3 temperature
T_∞	[°C]	Room temperature

The thermal problem was defined as transient three-dimensional heat diffusion equation with internal generation [5] and it was solved numerically using COMSOL software to obtain the temperature distribution in the core (Fig. 1).

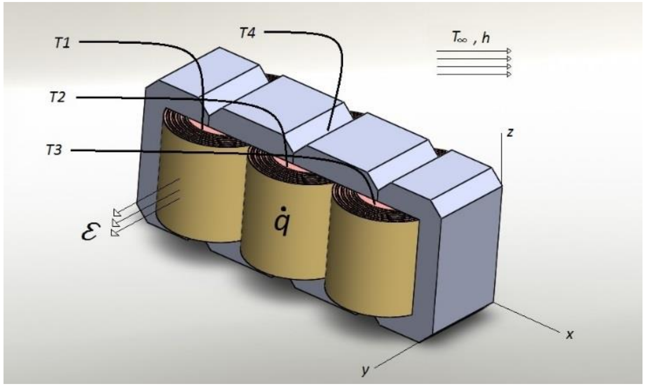
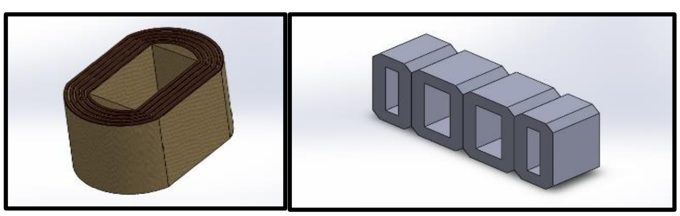


Figure 1 Thermal model of the core.

Initially the core assembly is at room temperature. When the load system is switched on, it starts heating which takes an average of 10 hours to reach the permanent regime. As already mentioned for thermal analysis, two load configurations, linear or non-linear, and two cooling configurations are imposed by natural convection and forced convection. From these configurations, a three-dimensional numerical model of the core set was developed in order to compare the results of temperatures calculated numerically with the measured temperatures at points where temperature sensors were placed. One of the main objectives of the numerical modeling of this problem is the possibility to determine the highest temperature points (Hot Spots) on the core and their coordinates. By accurately determining the temperature value of these Hot Spots, it is possible to better understand the problems that cause the transformer malfunction due to temperature excess. The geometry of the drawing was based as close as possible to the real model to ensure the highest precision of the simulation (Fig. 2). Points T1 to T4, according to Figure 1, were defined by the temperatures that presented the highest values in another experimental test [4]. It should be noted that these regions were also defined regarding the access for the insertion of the temperature sensors in the core.



a) b)

Figure 2 CAD draw of the a) windings and b) silicon iron.

EXTERNAL BOUNDARY CONDITIONS

The core is under convection and radiation on its outer surface. As already mentioned the loss of heat by convection occurs naturally or forcedly depending on the configuration of the ventilation. Thus for the numerical calculation of the temperature field, it is necessary to know the values of the average heat transfer coefficient by convection ($\bar{h}$). For this, empirical correlations taken from literature were used for the lateral and surface of the core. The heat transfer coefficient by convection also depends on the type of convection, forced or natural. Thus, for each type of convection there is an empirical correlation that allows calculating the value of this coefficient. From the value of the heat transfer coefficient, it is also possible to determine the heat flux on the desired surfaces. The studied core is usually placed inside a closed tank so in the normal operating condition only natural convection occurs. As previously mentioned, for simplification of calculations, the core was divided into two geometries: the winding was analyzed as a vertical cylinder (Fig. 2a) and the silicon iron core was analyzed as flat surface (Fig. 2b).

Boundary conditions are convection and radiation on all external surfaces of the transformer core.

$$-k\frac{\partial T}{\partial \eta} = h(T - T_\infty) + \sigma\varepsilon(T^4 - T_\infty^4) \tag{1}$$

where T is the temperature to be calculated numerically, η the normal direction, σ Stefan-Boltzmann constant, and T_∞ room temperature. The initial temperature condition for the thermal model of Fig. 1 is the uniform temperature condition equal to room temperature at t = 0. The values of thermal conductivity and thermal diffusivity vary according to the type of material in the core which may be copper, Kraft paper or silicon iron. Initially the core assembly is at room temperature, and when the load system is switched on, it starts heating. This takes an average of 10 hours to reach the permanent regime. As already mentioned for thermal analysis, two load configurations, linear or non-linear are imposed with natural convection. From these configurations, a three-dimensional numerical model of the core set was developed in order to compare the results of temperatures calculated numerically with the measured temperatures at the points where temperature sensors were placed.

NATURAL CONVECTION AND RADIATION

Considering the silicon iron piece, which makes up the core (Fig. 2b), the empirical correlation to determine $\bar{h}$ was the same as that used by Barroso [6]. To determine $\bar{h}$, it is necessary to find Nusselt number for the horizontal and vertical regions of the outer surface of the core.

Considering now the windings (Fig. 2a), whose geometries were approximated to that of a cylinder, the average heat transfer coefficient can be found from the correlation from Rahimpour and Azizian [7]. This correlation was used for Nusselt number Nu_c which is necessary to find the heat transfer coefficient by convection on the side of the cylinder $\bar{h}_c$.

EXPERIMENTAL APPARATUS

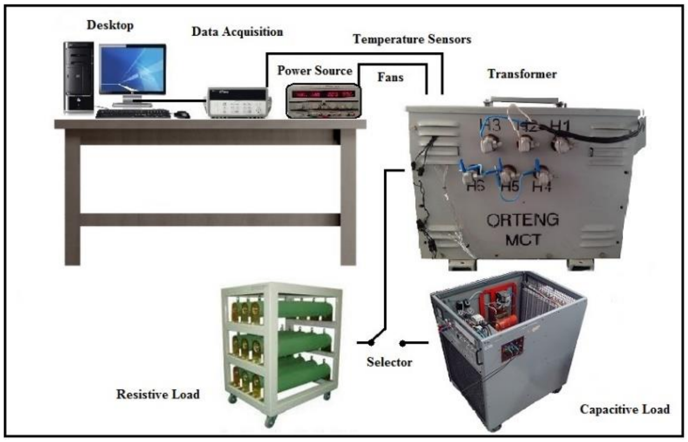


Figure 3 Experimental bench

Figure 3 shows the experimental apparatus developed for the load tests. The data acquisition system, controlled by a computer, is responsible for storing all the temperature data. The power supply provides the DC voltage needed to run the fans when testing with forced convection. The transformer is powered with a three-phase voltage of 220 volts. The loads are used separately depending on the required linear or non-linear configuration.

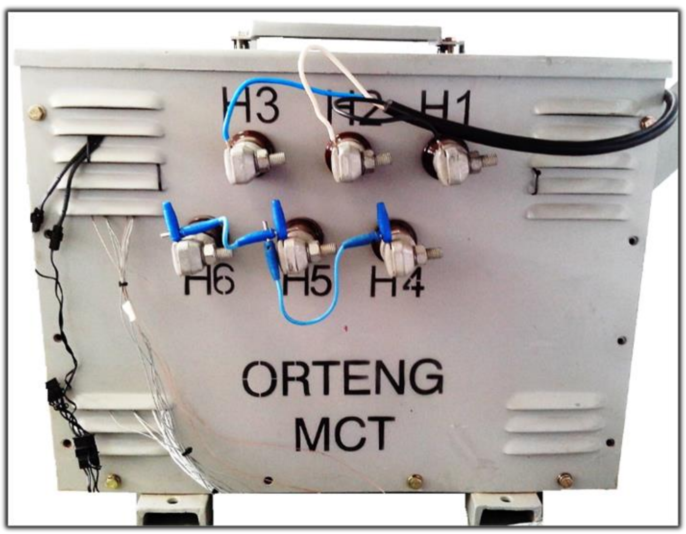


Figure 4 Transformer used in the tests

The three-phase dry-type transformer (Fig. 4) used in the tests was manufactured by Orteng and has nominal power of 5 kVA, standard NBR 10295. The voltage used is 220 volts. The transformer has thermal classification B that means the winding supports temperatures up to 130 ºC without damaging the insulation. The core is of the involved type, has ratio 1 to 1, that is, even number of spires in the primary and secondary windings, so the input and output voltages are equal. The material of the inductive part of the core is silicon iron alloy and the electrical connection of the transformer is made in (Y-Y). In the assembly, places to insert the temperature sensors were also selected which are: winding 1; winding 2; winding 3; surface of winding 2; inside tank.

Figure 5 shows the non-sinusoidal curve obtained by an oscilloscope; this curve represents a non-linear load.

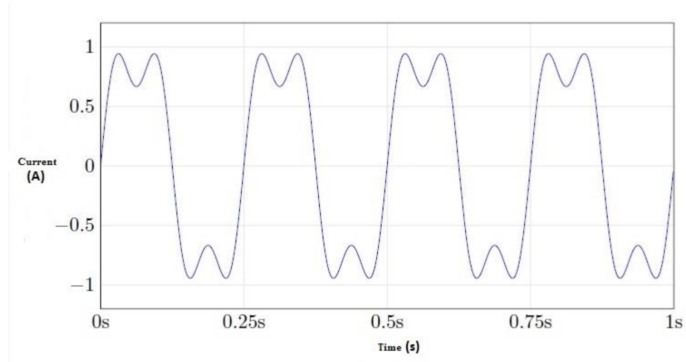


Figure 5 Non Linear Load Curve

NUMERICAL MODEL

The mesh used in all simulations has approximately 1.7 million tetrahedral elements. This mesh was chosen after conducting a mesh refinement test, summarized in Table 1. This test was carried out after the steady state was reached.

Table 1 Mesh refinement test.

Number of Tetrahedral Elements	Winding 2 Temperature (°C)	Simulation Time (min)
258617	127.35	196
545271	129.6	371
875452	135.56	562
1364912	135.88	891
1745736	135.99	1274

The COMSOL 5.2 software was used to simulate the distribution of temperature in the transformer from a three-dimensional model based as close as possible to the actual transformer dimensions and materials and also in the diffusion equations for both the transient and the permanent regime. The tetrahedral mesh generated by COMSOL for numerical simulation has 1764912 elements and is represented in Fig. 6. Accuracy is increased due to fewer voids in the winding mesh.

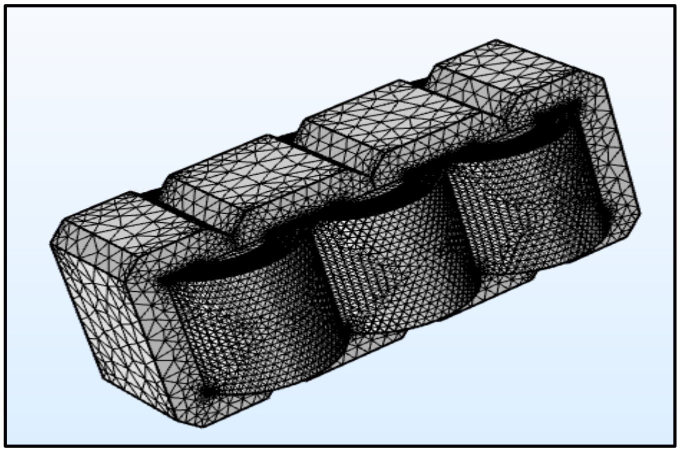


Figure 6 Tetrahedral mesh.

PROCESSING OF RESULTS

In order to guarantee the repeatability of the experimental temperature results, three tests were performed for each load and ventilation configuration, with 12 tests in total with approximately 25 hours each. In each experiment, approximately 1500 temperature points were acquired with a measurement interval of 1 minute. The tests where the temperature exceeded 130 ° C, the equipment required a special attention.

It was verified in the experiments that from approximately 700th min (11.6 hours) of test, the transformer reached the permanent regime. The temperatures measured by 7 sensors were obtained in real time by using the Agilent 34970A data acquisition. Figure 7 shows the four positions of the sensors on the core.

Figure 7 Position of Temperature Sensors

Table 2 shows the position and type of each sensor used in the tests.

Table 2 Type and position of temperature sensors.

Channel	Sensor Kind	Site	Coordenates (mm)
101	Thermocouple J	Winding 1	(-100,-61,45)
102	Thermocouple J	Winding 3	(100,-61,45)
103	Thermocouple J	Room Temperature	N/A
104	PT100	Winding 3	(100,-61,45)
105	PT100	Winding 2	(0,-61,45)
106	PT100	Winding 1	(-100,-61,45)
107	Thermocouple K	Winding 2	(0,-61,45)

TRENDS AND RESULTS

Figure 8 shows the experimental results of temperature during the heating and cooling period of the transformer. For this case, capacitive load was used supplying a charge of non-linear character. The highest temperature occurred in Winding 2 on sensor 107 (Type K Thermocouple) reaching 144.02 ° C. This temperature far exceeded the temperature limit of the transformer insulation of 130 °C, a demonstration that the use of non-linear load actually reduces the lifespan of the transformer since the insulation was not designed to reach these temperatures.

Figure 9 shows the experimental results of temperature during the heating and cooling period of the transformer. Resistive load was used supplying a charge of linear character. The highest temperature occurred in Winding 2 on sensor 107 (Type K Thermocouple) reaching 118.2 ° C.

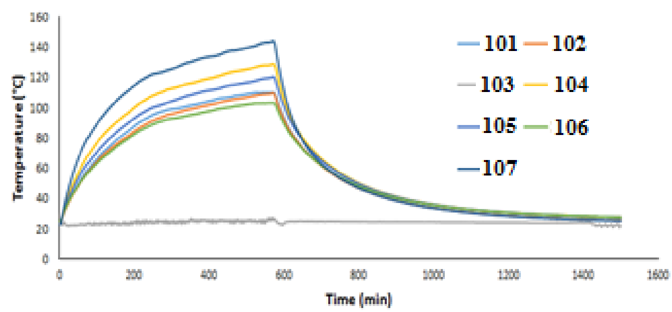


Figure 8 Temporal evolutions of the experimental temperatures in the transformer with non-linear load.

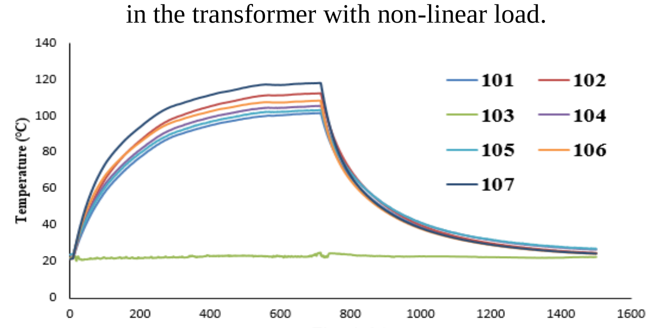


Figure 9 Temporal evolutions of the experimental temperatures in the transformer with linear load.

The internal generation used in the simulation was calculated from the heat transfer rate for each type of load by the equation $g = P/V$. It is necessary to divide this loss value of Watts by the volume of the winding (0.00126 m^3) so as to find the volumetric generation in W / m^3. For the linear load the internal generation is 91269 W / m^3 and for non-linear load it is 94912 W / m^3. The average heat transfer coefficients by convection are 6.49 W / m^2K for linear load and 6.83 W / m^2K for non-linear. For the radiation, the emissivity of 0.9 was obtained experimentally with a thermal camera model FLIR InfraCam. Initial temperature values were obtained from the experimental tests performed.

Figure 10 shows the temporal evolution of the temperature fields in the transformer core. The parts in red represent the highest temperatures near the center of the windings. Temperatures in the silicon iron parts are lower because the larger losses are concentrated in the windings. This simulation was done with the internal generations referring to the use of non-linear load with cooling by natural convection. This condition represents the most critical situation of core heating in the experimental tests.

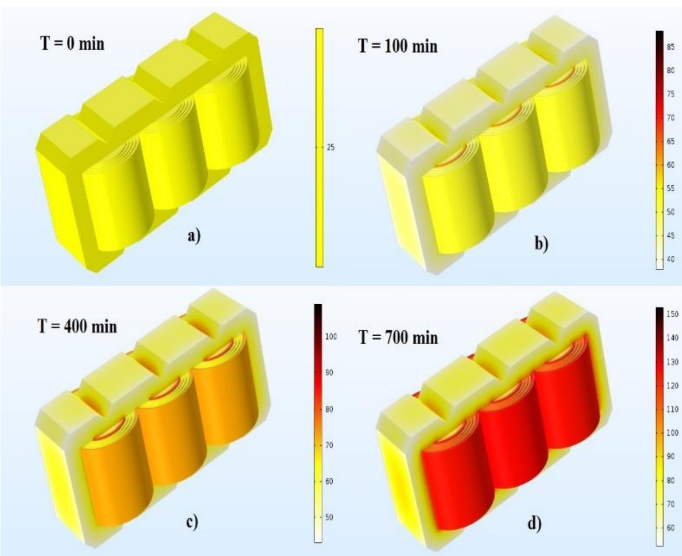


Figure 10 Temporal evolution of the temperature fields of the simulation for four time conditions.

From the data obtained with COMSOL, a comparison between the numerical and experimental results can be accomplished. In Fig. 11, a comparison between experimental and calculated temperatures is presented with the information referring to thermocouple in position 107. Figure 12 shows the residual values given by the percentage difference between the experimental and numerical temperatures.

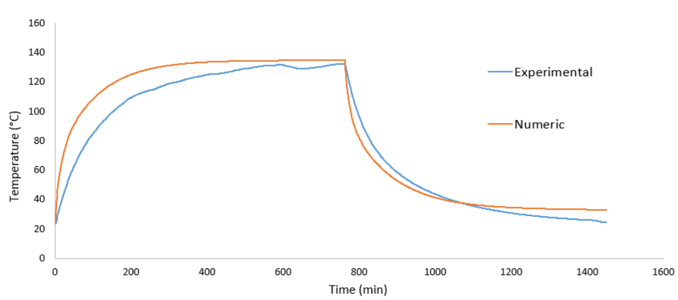


Figure 11 Comparison between numerical and experimental temperature for nonlinear load condition.

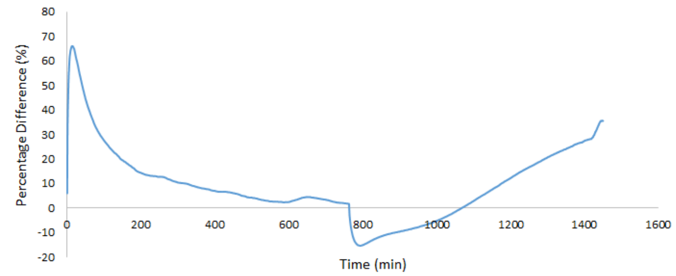


Figure 12 Percentage of the residuals obtained from the comparison of numerical and experimental temperature values.

HOT SPOTS

From the results of the temperature field provided by COMSOL, it was possible to determine the hot spots temperature for each type of load. Table 3 shows the Hot Spots for each type of load and their coordinates where the geometric center of the nucleus is the reference point (0,0,0). It is possible to notice that the maximum value of 153.29 °C occurs in the simulation with nonlinear load as expected. However, the value far exceeds the limit of 130 °C which is supported by the insulation of the transformer windings. This fact proves that the non-linear load is damaging to the life of the transformer.

The Hot Spots generated by linear loads did not reach the temperature limit of the insulation.

Table 3 Temperatures and Coordinates of the Hot Spots according to the nature of the load.

Load	Temperature (°C)	Coordenates (x,y,z)
Linear	109.25	(102.5;-63.43;0.63)
Non Linear	153.29	(103;-63.43;0.63)

Figure 13 represents the temperature distribution in the transformer core with the visual location of the Hot Spot.

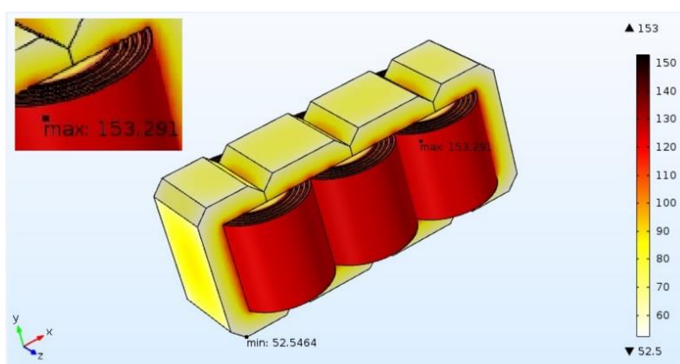


Figure 13 Hot spot location for non-linear load configuration

CONCLUSION

In this work, a methodology was presented for numerical and experimental analysis of the thermal behavior of the core of a 5 kVA dry-type transformer subjected to linear and non-linear loads. Another proof was that the thermocouples presented better results for temperature measurement, especially when the time was considered in the study, that is, the transient analysis. The numerical simulation using the COMSOL program proved its effectiveness by the proximity between the numerical and experimental temperature values. It was also possible to verify how the non-linear capacitive charge increases the temperature in the core. It was possible to quantify this increase as well as determine the location where higher temperatures occur. The numerical analysis allowed the determination of Hot Spots in the core for each type of load used.

The use of the empirical correlations from literature enabled to obtain the average heat transfer coefficient by convection. Another procedure that improved the results was the use of a thermographic camera to measure the emissivity of the transformer core and the knowledge of heat lost by radiation. Furthermore, the CAD design of the core geometry enabled the numerical analysis to be performed by using COMSOL. Therefore, the study of the transformer was possible with all the knowledge aforementioned.

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