# Considerations about Maximum Temperature of Toroidal Transformers in Steady-State Conditions

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**Abstract:** In this paper, a novel method based on a thermal mathematical model which includes the main geometrical, physical and thermal parameters of the toroidal transformer has been developed in order to obtain the maximum temperature inside the transformer during steady-state operating conditions. The influence of electric current and ambient temperature on the maximum temperature has been investigated. To validate the proposed method, some experimental tests have been done. The analyzed transformer had a rated power of 2kVA and the rated primary voltage of 230V. There is a good correlation between experimental and theoretical results with a maximum difference of 3°C.

**Keywords**: Toroidal transformers, Maximum temperature, Thermal analysis.

## 1. INTRODUCTION

The transformers have different configurations but the core shapes have two main types: EI laminations and toroidal cores. In selecting one, the criteria are the application, cost, efficiency, size, shape and volume. Toroidal construction has advantages related to size and volume as the winding occupies the full periphery of the core, resulting in reduced leakage inductance and stray magnetic fields and a lower air gap. The first transformer built by Faraday in 1831 had a toroidal core and even the first industrial-grade transformer was also wound in toroidal core (Ganz factory, in 1885). At present, toroidal transformers are to be found in modern applications, especially in the low-voltage or low power electronics equipments, audio systems and avionics. Although the toroidal transformers have many advantages over the classical ones, there are disadvantages to overcome in order to extend their use at medium and high power, as the cost, the difficulty of the winding and the limited published experience [1]. To study the thermal aspects of the transformers there are several thermal model, such as: hot spot temperature model, IEEE alternative thermal model, the top oil model, the ANSI top-oil-rise model, the semi-physical model, the Pierce's model, the thermal-electrical model, [2]. Classical transformers are largely studied from the point of view of thermal aspects, as in [2-4]. A survey of researches reveals the future trends and the continued interest in the application of advanced techniques for transformer design optimization. Artificial Intelligence techniques have been extensively used in order to cope with the complex problem of transformer design optimization, including toroidal core transformers [5]. The toroidal transformers are less studied, but there are comparisons between the thermal aspects for toroidal and conventional type transformers in various configurations, considering experimental analysis of the effect of temperature on parameters of power load [6].

In [7], the local losses were initially estimated from electromagnetic field analysis based on the Finite Element Method (FEM), then it used a method for recalculating the loss distribution based on the principle that the initial rate of rise in temperature at any point is proportional to the loss generated at that point. A steady-state thermal FEM using the previous resultant current densities allows to characterize the temperature distribution of the transformer with nonsinusoidal currents is presented in [8]. It is difficult to model a detailed structure of the toroidal inductor, partly due to the calculated cost, and for this there are studies to find a compact thermal modeling method of a toroidal inductor, especially as a part of switch mode power supply [9]. Genetic algorithms are used to study conventional laminated transformers [10] and toroidal core too [11]. The toroidal transformers are used in power electronic devices and their optimal design is considered to optimize the geometry, the operating frequency, the shape and the core material structure [12]. Optimizations of the toroidal inductors are studied in order to maximize the frequency of a given geometry and impedance as presented in [13]. An important difference between sinusoidal and PWM voltage excitation is a significant difference in the variation of instantaneous energy loss through the magnetising cycle which also contributes to the additional losses [14]. The toroidal transformers are used from usual and small power applications to special application at high-currents, as shown [15], where it is used as a multi-turn

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primary, single-turn secondary, current step-up toroidal transformer, with 5÷10 MAmps of peak current with pulse rise-time. The steady-state thermal analysis for toroidal transformers can be conducted using a lumped parameter model, which can be applied to small power and distribution-grade toroidal transformers, including the effects of the number of turns of windings, number of layers, insulation properties and geometric properties of the transformer as presented in [16, 17]. The toroidal design of the magnetic system of the inductor allows us to decrease the magnetic scattering field, avoid butt connections of the portions of the magnetic conductor, and increase the efficiency and the power coefficient [18]. The effect of temperature on toroidal transformers is studied under no-load condition into a climatic chamber to see the temperature influence on the value of RMS idle current and on the magnetization of the toroidal transformer [19]. Special applications could use the toroidal HTS (high temperature superconductor) transformers as described in [20]. Based on electrical and magnetic properties, such as saturation magnetization, initial permeability, and coercivity, in [21] are presented some considerations about the possibilities of applications of nanocrystalline alloys in toroidal cores for current transformers. Even the acoustic noise is studied for the toroidal transformers in audio and video equipment under normal and adverse mains conditions [22]. Some aspects related to the thermal radiation and natural convection during time variation conditions have been discussed in [23] and [24].

This study attempts to achieve and validate a new method to obtain the maximum value of the temperature inside the toroidal transformer during steady-state operating conditions. Actually, the paper proposes a novel mathematical model that includes the main geometrical, physical and thermal parameters of the toroidal transformer with the final goal to reach the maximum temperature.

## 2. METHOD TO ESTABLISH THE MAXIMUM TEMPERATURE AT TOROIDAL TRANSFORMERS IN STEADY-STATE CONDITIONS

The method for determining the maximum temperature in the steady-state conditions considers the particularities of the heating at coils wind up on ferromagnetic toroidal cores, the evolution of the maximum temperature depending on the electrical resistance of the structure and the thermal field in the area with the hottest temperature on the contours of their section, of the particularities of the thermal field in this case. The winding thickness is variable, and also the temperature of the cooling surface. The cooling surface area with the highest temperature also corresponds to the highest maximum of the winding volume temperature according to the laws of the thermal processes. Thus, with current means (electronic thermometers with thermocouples, infrared thermometers, thermal camera, etc.), we can detect the heated area in the steady-state conditions, under prescribed conditions and on the basis of measurements. Being aware of the construction of the toroidal electromagnetic device we can estimate the maximum temperature or maximum heating and can assess up to a maximum current up to which it can be used in steady-state conditions on the basis of the electric apparatus heating laws.

For the presentation of the method, a ferromagnetic toroid made from spiraled strip was considered, (Fig. **1**), with square section (rectangular or in steps included in the circumference of a circle), with toroidal winding (a winding or more). Section $S_{Fe}$ of the core is bounded by the radius $r_m$ and $R_m$ (inner and outer, respectively), and height $h_m$, and the winding is characterized by radius $r_b$ and $R_b$ ($g_x$ winding thickness is variable, with the $g_i$ value inside and $g_e$ value outside).

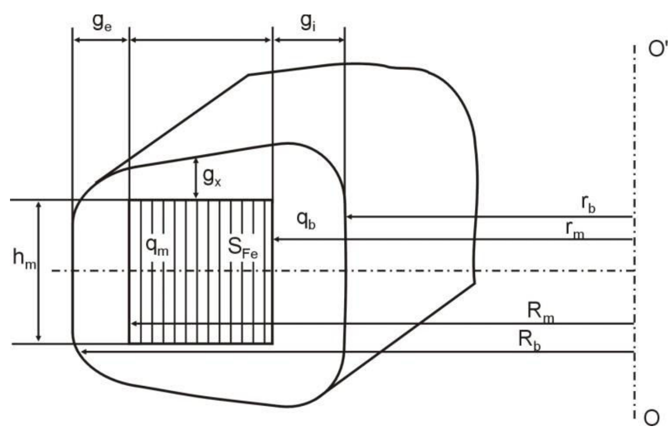


**Figure 1:** Cross section of a toroidal electromagnetic device.

Toroidal electromagnetic devices (coils with iron core, toroidal transformers, magnetic amplifiers, frequency multiplier, controlled inductive reactance, etc.), have the following features:

- the magnetic field in the core has the highest value on the circumference of radius $r_m$ and the smallest one on radius $R_m$ so that saturation gradually evolves from inside out;
- $q_m$ heat load in the core unit volume is variable and appropriate in all the volume, similar to the case from the area of the previously presented section;

- $g_x$ winding thickness is variable and unfavorable to cooling so that unitary thermal load from the volume, $q_b$, is variable with higher values at the interior where heat transfer is more difficult;
- the inner filling coefficient $k_{ui}$ is different respect to the outer filling coefficient $k_{ue}$, because the inside winding is made using turn close to the next turn, (Fig. **2**), which includes overlapping layers, while at the outside winding includes turns of different layers;
- the toroidal wind up position (vertical and horizontal) somewhat affects the cooling of the winding and the maximum heating zone.

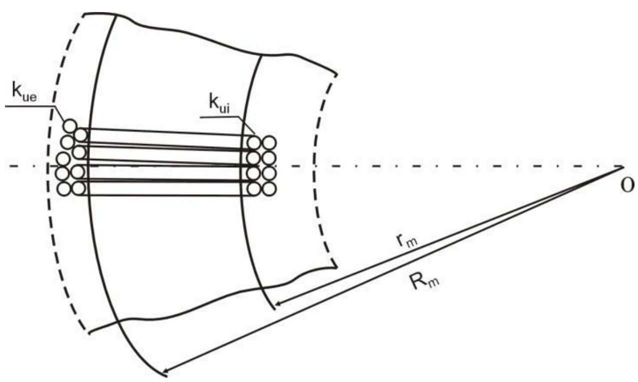


**Figure 2:** Constructive features of the toroidal winding.

It was considered as a case of natural cooling in the air with the toroid having a horizontal position. Under these conditions the cooling surface temperature of the coil (coils) depends on the point of measurement x, of the contour of the section in relation to a conventional origin, as outlined in Fig. (**3**), temperatures $\theta_m$, $\theta_1$, $\theta_2$... $\theta_7$, being caught at a certain electric current to the ambient temperature $\theta_a$. If there is only one winding, then the electric current is unique, and if they are several, we have a primary current $I_1$ and the currents $I_2$, $I_2'$...., of the secondary windings with the intensities corresponding to the transformation ratio on the primary winding.

To evaluate the cooling surface, preliminarily we use an equivalent sketch of the area of the toroidal winding section, with an average length $l_m$ of the winding turn, (Fig. **4**), for which the cooling area is:

$$A_{răcire} = A_{ci} + A_{ce} + 2A_c, \quad (1)$$

where:

$A_{ci} = 2\pi r_b h_b$ , is the inner cylindrical area of cooling of the coil, which may be overlooked when it is small or there are clamping pieces;

$A_{ce} = 2\pi R_b h_b = 2\pi R_b \left(2g_f + h_m\right)$, outer cylindrical area;

$2A_c = 2\pi\left(R_b^2 - r_b^2\right)$, circular cooling surfaces (upper and lower).

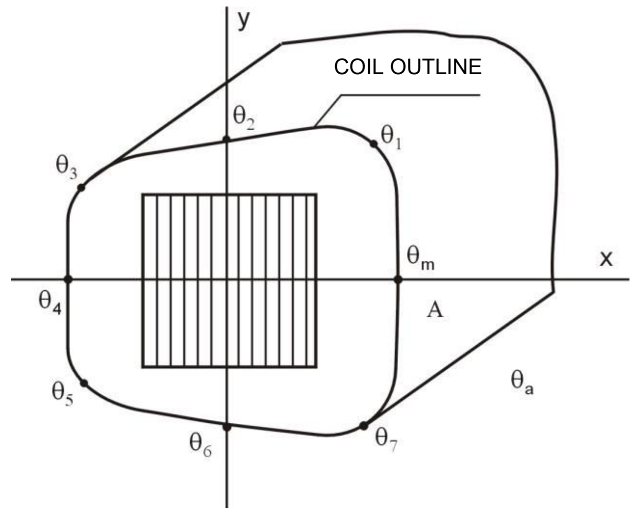


**Figure 3:** Measurement points of the temperature on the cooling line surface.

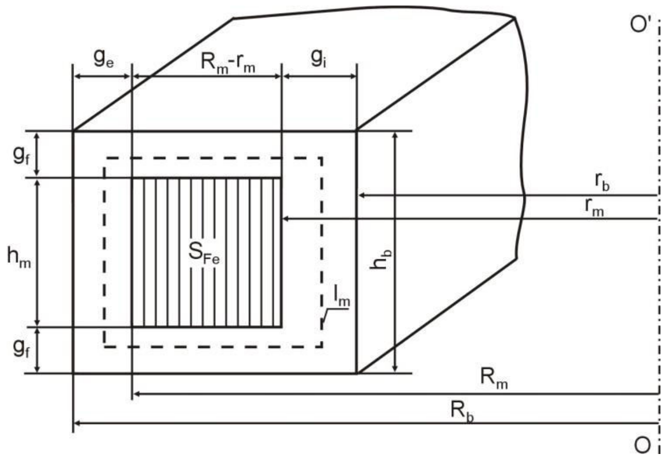


**Figure 4:** Equivalent sketch for a cros- section of a winded toroid to estimate the cooling surface.

With thermal Newton's law, preliminarily we may establish the heatings, $\vartheta$, for three currents ($I_1$, $I_2$, $I_3$), in steady-state conditions, with increasing values less than the rated current indicated by the manufacturer

$$\vartheta = \frac{P}{k_t A_r}\left[{}^\circ C\right], \quad (2)$$

where:

$P = RI^2$ [W], is the power dissipated in the coil, at the electrical resistance R [Ω], and current I [A];

$k_t$ = $10^{-3}$ [W/cm$^{2\circ}$C], total coefficient of heat transfer obtained from experimental tests [4];

$A_r$, cooling area [cm$^2$].

By measuring the ambient temperature θa, we can calculate the average temperatures of heating currents $I_1$, $I_2$ and $I_3$. With the electronic thermometer, the coil's surface was explored and the temperature was measured at a point A, (Fig. **3**), in which it has a maximum value, $\theta_m$, in the case of three currents. In order to get the information about time to reach the steady-state condition, it is necessary to calculate the thermal time constant of the winding [2]:

$$T = \frac{c_\gamma V_b}{k_t A_r} \text{ [s]}, \tag{3}$$

where:

$c_\gamma$ = 3.471 [Ws/cm$^{3\circ}$C], is the volume heat capacity for copper conductors;

$k_t$ = $10^{-3}$ [W/cm$^{2\circ}$C], total coefficient of heat transfer;

$V_b$, the winding's volume, [cm$^3$], calculated using the equivalent drawing, (Fig. **4**);

$A_r$, cooling area [cm$^2$].

After a time t = 4T, it is considered to reache a steady-state condition. Practically, identifying the hot point on the surface winding, it can be established the maximum temperature rise (the maximum temperature, respectively) at the certain current and therefore, it can be evaluated the insulation class of the built winding. The maximum allowed current $I_i$, at ambient working or calculus temperature, $\theta_a$, reported at rated ambient temperature, $\theta_{an}$, is calculated with the formula [3]:

$$I_i = I_s \sqrt{\frac{\theta_i - \theta_{an}}{\theta_s - \theta_a}} [A], \tag{4}$$

where:

$\theta_s$ means the temperature measured in unstedy conditions at heating current $I_s$ and ambient temperature $\theta_a$;

$\theta_i$, admissible temperature coefficient;

$\theta_{an}$, rated ambient temperature.

In Fig. (**5**), the curve θ(x) represents the evolution of the temperature into winding thickness recorded at a time-moment prior to reaching the steady-state conditions, and the curves $\theta_1(x)$ and $\theta_1^{'}(x)$ express the temperature distribution in coil's thickness under steady-state conditions for two values of heating current, $I_1^{'} > I_1$. It was observed a difference between maximum temperatures during steady-state conditions, $\theta_{m1}^{'} > \theta_{m1}$, in the magnetic core area characterized by inner radius $r_m$. The same difference can be noticed at the minimum temperature values, $\theta_1^{'} > \theta_1$.

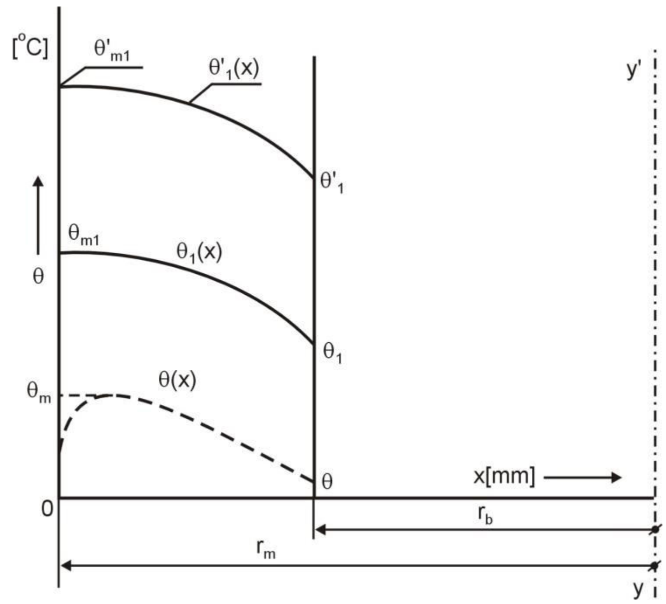


**Figure 5:** Temperature variation within winding cross section.

Analytical expression for the characteristic $\theta_1(x)$, or $\theta_1^{'}(x)$, is:

$$\theta_1(x) = -C_1 x^2 + 2C_1 x_m^2 \ln x + C_2, \tag{5}$$

where:

variable x, belongs to the range ($r_m$ - $g_b$)...($r_m$ - $g_{iz}$), in which $g_b$, means winding thickness and $g_{iz}$, the insulation thickness located on the ferromagnetic toroidal core;

$x_m = r_m - g_{iz}$, coordinate x, at which winding's temperature is the maximum;

$C_1 = \frac{q}{4\lambda}$, constant to be computed in which:

$q = \frac{j^2 \rho_\theta}{v_1}$, is the density of the heat flux in the area (j - current density, $\rho_\theta$ – conductors resistivity at the temperature to be reached, $v_1$ - unit volume);

$\lambda = 0.6\lambda_i \dfrac{d}{2\delta}$, the equivalent thermal conductivity ($\lambda_i$ – coefficient of thermal conductivity for the insulation, d – conductor diameter, δ – insulation thickness);

$C_2$, constant which is established at limit conditions, $\theta = \theta_s$, value to be measured. Results:

$$C_2 = \theta_s + C_1(r_m - g_b)^2 - 2C_1(r_m - g_{iz})^2 \ln(r_m - g_b) \quad (6)$$

The method is easy to be applied in order to check the thermal behaviour of a series of coils with iron core or toroidal transformers, because on the core prototype it will be mounted a series of thermocouples, it will draw the $\theta_m(x)$ characteristic, in the hottest area and then in the case of toroidal transformers without thermocouples it will measure the temperature in the same hottest area under prescribed conditions and it will obtain $\theta_m(x)$ curve.

Knowing the temperature of the steady-state conditions in at least three values of heating current, $I_1$, $I_2$ and $I_3$, we may establish the heating characteristics in the steady-state conditions, θm (I), of the hottest area in case of θa ambient temperature, the measured value, and at rated ambient temperature, θan, with the expression:

$$\theta_m = \theta_a + kI^2, \text{ or } \theta_m' = \theta_{an} + kI^2, \quad (7)$$

where k is a constant that results by knowing the maximum values of the temperature at the corresponding heating currents.

From this characteristic, we can estimate the maximum allowable heating current for a particular class of insulation in which the toroidal winding has been built.

The method has the following advantages:

- it allows the establishment of a maximum temperature of the area in which it is located with the guess of the maximum permissible assessment of the current that goes through the winding or windings;
- establishes the need to use heatsinks for heat transmission when it exceeds the possibilities of natural heat transfer/cooling;
- the measurements can be made progressively at lower currents than the rated current value so that it can be verified if the prescribed current can be supported or not;
- at mass and repetitive manufacturing, the production capability of the manufacturer along with the established measures can be established to improve the manufacturing technology.

## 3. EXPERIMENTAL TESTS

By knowing the geometric dimensions of the magnetic circuit, winding, winding resistances, and material constants, the average heating was calculated using the regard (2) through a program developed in MATLAB release 7.1, at four intensity values of primary current, $I_1$ = 3, 6, 8 and 9A, which crosses the winding with 270 turns, corresponding to the tap necessary to decrease the load voltage. The currents from the secondary, corresponding to the values in the primary, had the measured values of 18, 34, 44 and 50A. Also, in order to measure the temperature and the heat inside and on the winding, three thermocouples of iron-constantan with low thermal inertia were provided:

- on the magnetic core surface, at the middle height, inwards;
- between the primary and secondary winding, at half-height, inwards;
- on the winding's surface, being able to move around all the outside contour.

To increase the accuracy of measurements, it was used as data acquisition board type DAQ NI connected to a PC with the following characteristics:

- analog inputs: 16 (8 differential channels), 12 bits resolution, sampling rate 250kS/s ;
- analog outputs: 2, on 12 bits ;
- digital inputs/outputs: 8 ;
- counters / timers: 2, on 24 bits ;
- triggering: analogue, digital, start/stop;
- advanced control, PID adjustment, specific functions incorporated.

Such data acquisition boards can be programmed using the specialized graphical software environment, LabVIEW release 8.1. To measure temperatures from thermocouples, an application has been developed as presented in the figure below, (Fig. **6**).

As can be seen from the figure, the main panel (front panel) allows measurement of the current from the primary and secondary auxiliary transformer and the maximum temperatures between windings and on

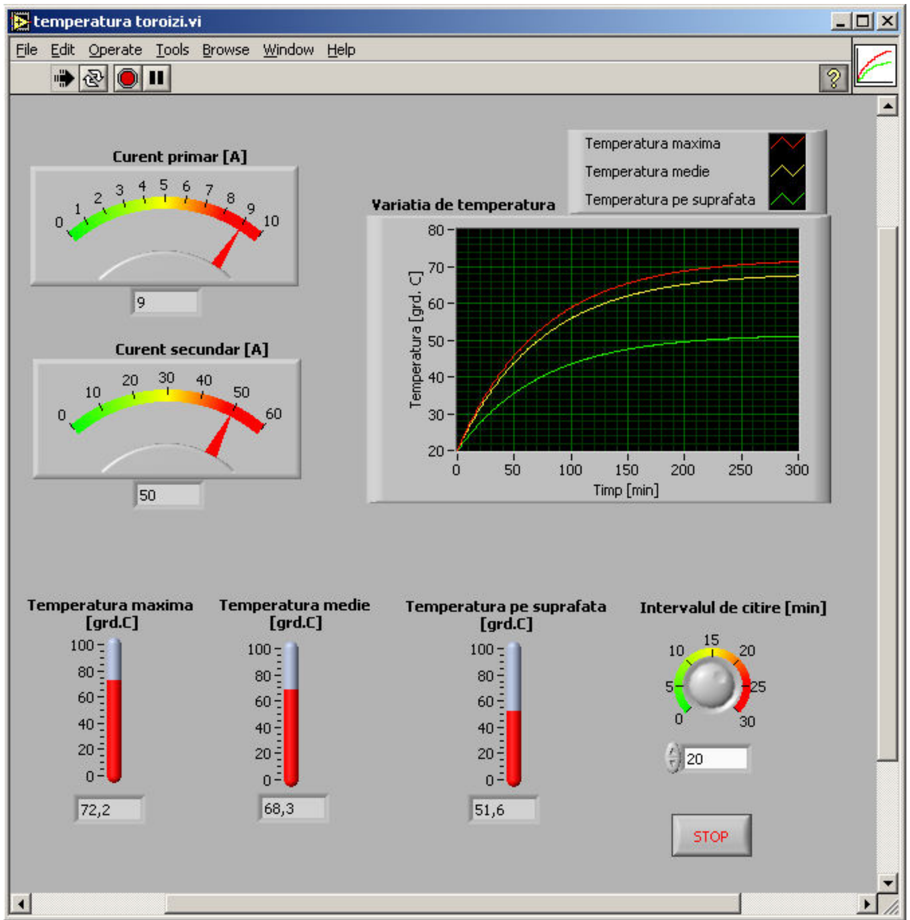


**Figure 6:** LabVIEW application to measure the temperatures of auxiliary transformer toroidal type.

the toroids' surface, which are the analog inputs to be subjected to a value of maximum 10Vdc, for protection in voltage of the data acquisition board. It can also be set at the reading interval of the temperature values, depending on the time constant of toroidal transformers. It can record the time evolution of the temperatures; instantaneous values are displayed on the front panel of the application, (Fig. **6**). Using the temperature information taken from the thermocouple mounted between the primary and the secondary winding, the average heating was determined so the values are summarized in the Table **1**, compared with those obtained from calculations.

**Tabel 1: Comparison between Computed and Measured Average Heating Values**

| $I_1$[A] | 3 | 6 | 8 | 9 |
|---|---|---|---|---|
| $I_2$[A] | 18 | 34 | 44 | 50 |
| $\vartheta_{calc}[^\circ C]$ | 6.31 | 23.47 | 40.29 | 70.59 |
| $\vartheta_{mas}[^\circ C]$ | 5.90 | 22.40 | 38.80 | 68.30 |

It was observed that there is a satisfactory concordance between the calculated and measured values, with a recorded difference of less than 3ºC. This is explained by the fact that the only the tap winding with 270 turns from the primary has been supplied. Actually, to the heating process, it was participated only a slightly more than half of the primary winding, with a total of 510 turns, the rest of the turns have been involved to the heat dissipation. This explains the lower measured values than those calculated.

Using the equations (5) and (6), an analytical expression is formed for the maximum temperature he depending on the winding surface. The temperature can be measured and the formal expresion is:

$$\theta_{\max} = \theta_s - \frac{q}{4\lambda}\left[(r_m - g_{iz})^2 - (r_m - g_b)^2\right] + \frac{q}{2\lambda}(r_m - g_{iz})^2\left[\ln(r_m - g_{iz}) - \ln(r_m - g_b)\right] \quad (8)$$

Using the thermocouple mounted on the core and the one on the surface side of the winding, we have obtained the following values measured and calculated for maximum temperature.

**Tabel 2: Comparison between Computed and Measured Maximum Temperature Values**

| $I_1$[A] | 3 | 6 | 8 | 9 |
|---|---|---|---|---|
| $I_2$[A] | 18 | 34 | 44 | 50 |
| $\theta_{mcalc}[^\circ C]$ | 28.30 | 45.50 | 63.10 | 74.50 |
| $\theta_{mmas}[^\circ C]$ | 26.00 | 43.10 | 61.00 | 72.20 |

Also, in this case, there are observed close values between the measured and the calculated ones, analyticcal expression providing a very good picture of the evolution of temperature at the toroidal transformer analyzed.

As can be noticed from the above Tables 1 and 2, there are normal differences between computed and measured values. The differences can be explained because of the simplified mathematical model for the thermal analysis of the toroidal transformer during steady-state conditions and on the other hand, because of the experimental set-up, mounting conditions of the thermocouples, measurement errors, etc.

Knowing the maximum temperatures in the steady-state conditions related to the heat currents values (for instance, in the secondary winding of the toroidal transformer) it can be estimated the temperature rise characteristics, $\theta_m$(I) in the case of ambient temperature $\theta_a$. The same temperature rise characteristics can be obtained in the case of rated ambient temperature, $\theta_{an}$ if the expression (7) will be used. Measurements were performed at ambient temperature of 20ºC, resulting in the characteristics from Fig. (**7**).

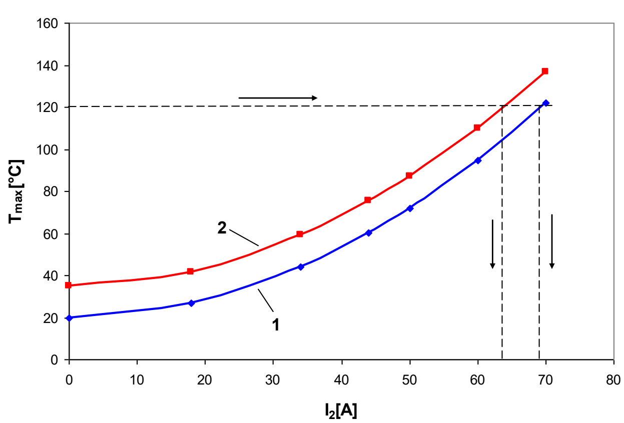


**Figure 7:** Heating characteristic in steady-state conditions in the case of ambient temperature (curve 1), and rated ambient temperature (curve 2).

If we consider a winding with E class insulation, so the maximum temperature is 120°C, then it may obtain from Fig. (**7**) the maximum current that could flow through the secondary winding in the case of ambient temperature by 20°C, $I_2$ = 69.33A. For a rated ambient temperature 35°C, it gets the current value, from the same Fig. (**7**), $I_2$ = 63.92A. Thus, it results an overload coefficient,

$$k_i = \frac{I_{2\max}}{I_{2n}} = \frac{69.33}{57.7} = 1.2 \tag{9}$$

at ambient temperature of 20ºC, respective,

$$k_i' = \frac{I'_{2\max}}{I_{2n}} = \frac{63.92}{57.7} = 1.1 \tag{10}$$

at rated ambient temperature 35 ºC. So, during steady-state conditions, the load current through the secondary winding of the auxiliary transformer can increase the maximum 1.2 times at the ambient temperature of 20°C.

## 4. CONCLUSIONS

Following the thermal analysis performed at the toroidal transformer, the following conclusions can be deduced:

- it was established as an original method for determining the maximum temperature at toroidal transformers in steady-state conditions;
- confirmation of the results obtained by calculation was performed by measurements of temperatures recorded through a data acquisition board connected to the PC, the differences between the measured values and those calculated were less than 3ºC, at average heating, and also there have been differences of less than 2.5ºC at the maximum temperatures;
- there is the possibility of current overloading with a coefficient of 1.2, at ambient temperature of 20ºC, or with a coefficient of 1.1, for the rated ambient temperature of 35ºC;
- the next work will perform a thermal transient analysis of the toroidal transformer starting from mathematical model during steady-state conditions including the time variation of main parameters.

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