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Investigations on the Influence of Selected Factors on Thermal Parameters of Impulse-Transformers

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Abstract: In the paper the results of experimental investigations illustrating the influence of the selected factors on parameters of the thermal model of the transformer are presented. The form of this model and the applied method of measurements of the transformer structural components' self and mutual transient thermal impedances are described. The influence of the selection of material of the core, its geometrical dimensions, spatial orientation, shape of the core, frequency of the primary winding current in the transformer and power lost in this element on the considered thermal parameters of the transformer are discussed. An analytical formula describing the dependence of the considered transient thermal impedances on the internal temperature of the windings is proposed and verified experimentally.

Keywords: thermal parameters;selfheating; impulse-transformers

Vplivi izbranih parametrov na termične parametre impulznih transformatorjev

Izvleček: Članek prikazuje rezultate eksperimentalnih raziskav vplivov izbranih faktorjev na parameter termičnega modela transformatorja. Opisan je model, uporabljene merilne metode in vzajemne tranzientne termične impedance. V smislu termičnih parametrov so obravnavni: izbira materiala jedra, geometrija, orientiranost, frekvenca toka primarnega navitja in izgube. Predlagana in eksperimentalno preverjena je analitična enačba odvisnosti tranzientne termične impedance od temperature navitja.

Ključne besede: termični parametri; lastno segrevanje; impulzni transformator

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1 Introduction

Impulse-transformers are commonly used in switched-mode power electronic converters [1, 2, 3, 4]. The considered elements have a simple construction - they consist of the ferromagnetic core and windings. The properties of both these components influence temperature, the change of which causes changes of the value of technical parameters of the core and windings [4, 5]. Particularly, when the core temperature is higher than the Curie temperature, magnetic permeability of the ferromagnetic core decreases to the value near permeability of free air, and the transformer practically does not transfer energy from the input to the output. In turn, the excess of the admissible temperature of windings can cause destruction of isolation of winding wires [4, 5], leading to the short-circuit of turns.

The temperatures of the core and windings of the transformer during its operation are higher than the ambient temperature as a result of self-heating in the core and in the winding [5-14], as well as mutual thermal coupling between them. Calculating values of temperature of structural components of the transformer demands using the thermal model. Such a model can have the form of the detailed model, making it possible to calculate time-space distribution of temperature in the considered element [9-12, 15], or the compact model - making possible calculations of waveforms of temperature of this element [6, 13, 14] or the selected structural components of the transformer [5, 7]. In the paper [13] many results of calculations of temperature distribution in a planar transformer obtained with the use of the finite element method (FEM) are presented. In these calculations uniform distributions of the pow-

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er dissipated in the core and in the windings were assumed. The results of measurements shown in this paper prove that this assumption is fulfilled.

In the case of the use of the compact thermal model it is indispensable to measure the transformer's self and mutual transient thermal impedances. Thermal models presented in papers [5, 6, 7, 8, 13] are linear models, i.e. transient thermal impedances in these models neither depend on constructional factors nor on the power lost in the transformer. Yet, in papers [16, 17, 18] (for instance) it was shown that thermal parameters of semiconductor devices strongly depended, among other things, on the power dissipated in them, the type of the case, or the manner of mounting the considered device. It can be expected that a similar influence will be observed in the case of magnetic elements, to which the transformer belongs.

In the paper the method to measure thermal parameters existing in the thermal model of the transformer and the results of measurements of these parameters illustrating the influence of the selected factors on efficiency of transformers cooling are presented. Transformers with ring cores considered in the present paper are characterized by uniform distribution of the magnetic force and magnetic flux density, similarly as transformers considered in paper [13]. Therefore, distribution of power density in the core is also uniform.

In Section 2 the form of the thermal model of the transformer is presented and the transformer's self and mutual transient thermal impedances are defined. Section 3 contains a description of the measuring method to measure the transformer's self and mutual transient thermal impedances. In Section 4 the results of measurements of thermal parameters of the selected constructions of transformers are presented and the analytical formula describing the influence of the dissipated power on the considered parameters is proposed and experimentally verified.

2 Thermal Model of Transformer

The thermal model describes the dependence of the internal temperature of the electronic component on the power emitted in it. In the case of commonly used compact thermal models this dependence can be described by means of the convolution integral [19, 20, 21]. As it is shown, among other things, in papers [5, 7, 22], in order to describe correctly thermal properties of magnetic elements it is indispensable to take into account both self-heating in the core and in windings, as well as mutual thermal coupling between them. Hence, the temperature of k-th winding can be described by the following formula

$$T_{wk}(t) = T_a + \sum_{j=1}^{n} \int_0^t Z'_{thwkj}(t) \cdot p_j(t-\tau) d\tau + \int_0^t Z'_{thck}(t) \cdot p_c(t-\tau) d\tau \quad (1)$$

where T_a denotes the ambient temperature, k represents the name of the winding, $p_k(t)$ denotes the power dissipated in k-th winding of the transformer and $Z'_{thwkj}(t)$ represents the time derivative of the devices' self (for k = j) or mutual (for k $\neq$ j) transient thermal impedance between the windings of the transformer, n – the number of windings, $Z'_{thck}(t)$ – the time derivative of mutual transient thermal impedance between the core and the k-th winding, whereas $p_c(t)$ is the power dissipated in the core.

In turn, the temperature of the core is given by the following formula

$$T_c(t) = T_a + \sum_{j=1}^{n} \int_0^t Z'_{thcj}(t) \cdot p_j(t-\tau) d\tau + \int_0^t Z'_{thc}(t) \cdot p_c(t-\tau) d\tau \quad (2)$$

where $Z'_{thc}(t)$ is the time derivative of the core's self transient thermal impedance.

The core's self or mutual transient thermal impedance can be modelled using the classical formula [19, 23, 24]

$$Z_{th}(t) = R_{th} \cdot \left[1 - \sum_{k=1}^{N} a_k \cdot \exp\left(-\frac{t}{\tau_{thk}}\right)\right] \quad (3)$$

where R_{th} is thermal resistance, τ_{thk} denotes k-th thermal time constant, a_k is the ratio factor corresponding to this time constant, whereas N is the number of thermal time constants.

The presented thermal model, given by equations (1 – 3) of the transformer can be described as the RC electrical analog, like the linear thermal model presented in [5]. In the real situation, where the parameters existing in Eq. (3) depend on the value of the dissipated power, the nonlinear thermal model is needed. The simple form of this model for the electronic device non-coupled thermally with any other device is proposed in [17]. In this model, the controlled voltage and current sources are used instead of RC elements.

3 Method to Measure Thermal Parameters of the Transformer

The transformer's self and mutual transient thermal impedances of the selected magnetic devices were measured with the use of the method described in papers [25, 26]. This method is realised by means of the measurement set presented in Fig.1.

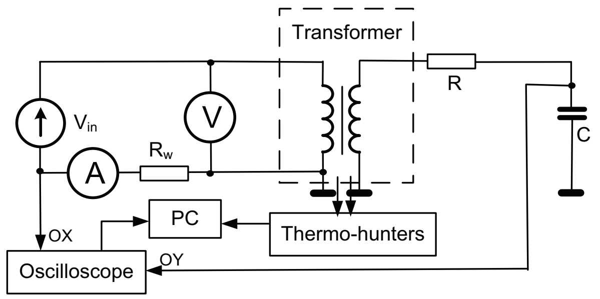


Figure 1: Measurement set for measuring thermal parameters of the transformer [26]

The measurements are realised in two steps. The first step needs stimulations of the primary winding with a current step and the measurement of waveforms of the windings temperature and the core temperature by means of thermo-hunters (pyrometers with IR sensors) until the thermally steady-state is achieved. In the considered measurement set the thermo-hunters of the type PT-3S by Optex are used [27]. The range of the measured temperature is from 0 to 200 °C and the resolution is equal to 0.1°C. These thermo-hunters are situated in the distance of 25 mm from the measured transformer. The area, on which the temperature is measured, has the form of a circle with the diameter 2.5 mm. During measurements it was assumed that emissivity of all components of the considered transformers has the constant value equal to 0.95. This value is close to typical values of emissivity of materials used to construct transformers.

As it results from the Authors' investigations presented in [26], in the area of a transformer, in which the windings are located, practically uniform distribution of the temperature is observed. Similarly, temperature distribution of the core is quasi-uniform. Therefore, averaging the temperature value in a circle of the diameter equal to 2.5 mm does not cause a visible measurement error.

The waveforms of the core temperatures $T_C(t)$ and of the winding temperature $T_W(t)$ while heating the transformer are registered by the computer PC coupled with two thermo-hunters. By means of the voltmeter and the ammeter the values of the voltage on the primary winding V_1 and the current of this winding I_1 are measured at the steady-state. The results of these measurements are used to calculate transient thermal impedance of the winding $Z_{thW}(t)$ and mutual transient thermal impedance between the core and the windings $Z_{thWC}(t)$ with the following formulas

$$Z_{thW}(t) = \frac{T_W(t) - T_a}{V_1 \cdot I_1} \tag{4}$$

$$Z_{thWC}(t) = \frac{T_C(t) - T_a}{V_1 \cdot I_1} \tag{5}$$

where T_a is the ambient temperature.

In the second step, the primary winding of the transformer is stimulated by a sinusoidal signal of frequency f_s, whereas the temperature of the core is measured by the thermo-hunter. When the steady state is obtained, the hysteresis loop of the magnetising characteristic B(H) of the core is measured using the oscilloscope and next - transmitted to the computer (PC).

The waveforms of the magnetic force H(t) and flux density B(t) are calculated using the following formulas

$$B(t) = \frac{R \cdot C \cdot u_C(t)}{z_2 \cdot S_{Fe}} \tag{6}$$

$$H(t) = \frac{z_1 \cdot i_1(t)}{l_{Fe}} \tag{7}$$

in which R and C denote resistance of the resistor and capacitance of the capacitor used in Fig.1, respectively, z_1 and z_2 are numbers of turns in primary and secondary windings, respectively, S_{Fe} – the cross-section area of the core, l_{Fe} – magnetic path in the core, u_C – voltage on the capacitor C, whereas i_1 – the current of the primary winding.

The area S_H of the obtained hysteresis loop B(H) is given by following formula

$$S_H = \oint B dH \tag{8}$$

This integral is calculated using the Excel software and the method of numerical integration. The used values of frequency f_s are in the range from 1 kHz to 100 kHz. Next, in the moment t = 0 the power supply of the primary winding is switched off and waveforms of the core temperature $T_C(t)$ are measured until the steady state is obtained. The transient thermal impedance of the core $Z_{thC}(t)$ is calculated using the following formula

$$Z_{thC}(t) = \frac{T_C(t=0) - T_C(t)}{V_C \cdot f_s \cdot S_H} \quad (9)$$

where V_C represents volume of the core. In Eq. (9) only the power dissipated in the core is taken into account, whereas the power dissipated in the windings is omitted. This is justified, if the value of the power dissipated in primary and secondary windings is much smaller than the power dissipated in the core. Such conditions are fulfilled when

$$S_H \cdot f \cdot V_C >> I_1^2 \cdot R_1 + I_2^2 \cdot R_2 \quad (10)$$

where I_1 and I_2 are RMS values of primary and secondary windings currents, whereas R_1 and R_2 are resistances of these windings.

4 Investigation Results

Using the method presented in Section 3, measurements of thermal parameters of transformers containing ferromagnetic cores made of the powdered iron (RTP), the ferrite (RTF) and the nanocrystalline cores (RTN) were performed.

The first series of measurements was performed for ring cores of the dimensions RTP 26.9x14x11 made of material T106-26, RTN-26x16x12 made of material M-070, RTF-25x15x10 made of material F-867, called in the further part of this paper small ring cores. The second series of measurements was made for cores made of the same ferromagnetic materials, but of the bigger dimensions: RTP 39.9x24.1x14.5 made of material T157-26, RTF 40x24x16 made of material F-867, called in the further part of this paper large ring cores and for the pot core B65701 -T1000-A48 of the diameter 30 mm and heights 19 mm made of material N48. In Table 1 the values of basic parameters of the considered ferromagnetic materials are collected. In this table B_{sat} denotes saturation flux density at the magnetic field strength H_{sat}, H_C is the coercive field strength, T_C – Curie temperature, whereas P_V – relative core losses.

In marking ring cores each number means the outside diameter, the inside diameter and the height of the core expressed in millimetres, respectively. The view of the ring core with its dimensions is shown in Fig. 2, whereas the view of the pot core is shown in Fig. 3. The temperature of windings of the transformer with the pot core can be measured using a hole in this core.

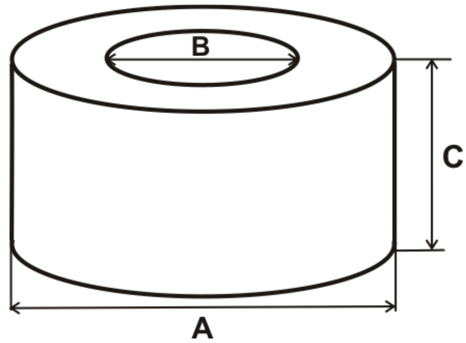


Figure 2: View of the ring core with its dimensions

On small ring cores two windings containing 22 turns were wound with copper wire in the enamel of the diameter 0.8 mm. In turn, on large ring cores two windings containing 30 turns of copper wire in the enamel of the diameter 0.8 mm were wound. The transformer with the pot core contains two windings made with the same wire consisting of 22 turns. The views of transformers with the ring core and with the pot core are shown in Fig. 4 and Fig. 5, respectively.

As it is visible, the distance between turns in each winding is not constant. The temperature of these windings is measured for the area in which this distance is the smallest and much smaller the measuring spot of the used thermo-hunter.

In the following figures the results of measurements of self and mutual transient thermal impedances $Z_{th}(t)$ of the selected constructions of impulse transformers (solid lines) and approximation of these curves (dashed lines) with Eq. (3) are presented. The values of parameters of the model described with the equation (3) are estimated with the use of the method proposed in [5]. The value of R_{th} is estimated by averaging the wave-

Table 1: Values of basic parameters of the considered ferromagnetic materials

parameter	T106-26 and T157-26	M-070	F-867	N48
manufacturer	Micrometals	Magnetec	Ferystec	Epcos
B_{sat} [T]	1.38	1.2	0.5	0.42
H_{sat} [A/m]	19.9x103	590	966	1200
H_C [A/m]	440	9	75	26
T_C [°C]	750	600	215	170
P_V [kW/m³]	180 @f=100 kHz	800 @f=100 kHz	400 @f=100 kHz	-

form of the considered transient thermal impedance in the steady state (typically for the last 100 seconds), whereas the values of the parameters a_i and thermal time constants t_{thi} are determined by the least square method. Starting from the longest thermal time constant through approximation based on the formula [5]

$$y_i(t) = \ln\left(1 - \frac{Z_{th}(t)}{R_{th}} - \sum_{j=1}^{i-1} a_j \cdot \exp\left(-\frac{t}{\tau_{thj}}\right)\right) \quad (11)$$

the linear function given by

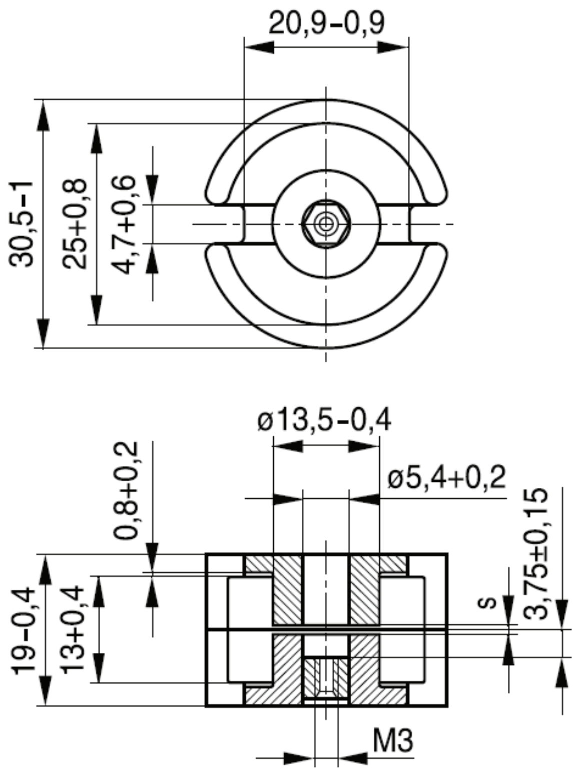


Figure 3: Cross-sections of the pot core B65701 -T1000-A48 with its dimensions

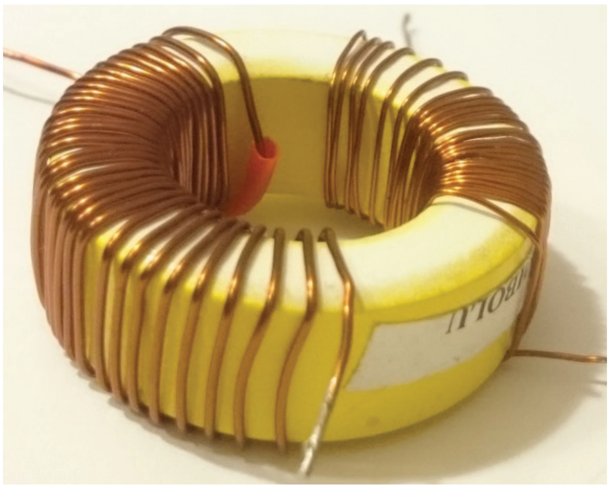


Figure 4: View of the transformer with the ring core

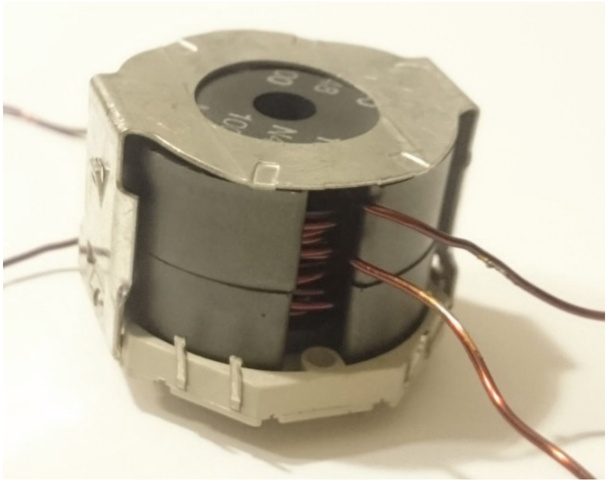


Figure 5: View of the transformer with the pot core

$$y_i(t) = -\frac{t}{\tau_{thi}} + \ln(a_i) \quad (12)$$

is used.

Attention is focused on the parameters describing self-heating phenomenon in the core ($Z_{thC}(t)$) and in the winding ($Z_{thW}(t)$), as well as mutual thermal coupling between the core and the windings ($Z_{thWC}(t)$). The mutual thermal couplings between the windings are not taken into account.

The values of parameters R_{th}, a_i, τ_{thi} approximating the selected waveforms of the investigated transformers' self and mutual transient thermal impedances are collected in Tables 2 - 5.

Table 2: Parameters values of transient thermal impedances in transformers with the small ring core RTP situated horizontally

parameter	$Z_{thW}(t)$	$Z_{thWC}(t)$	$Z_{thC}(t)$
R_{th} [K/W]	22.15	18.12	25.39
a_1	0.664	0.758	0.925
a_2	0.206	0.242	0.068
a_3	0.13		0.007
τ_{th1} [s]	661.2	710.5	702.1
τ_{th2} [s]	134.1	259	283
τ_{th3} [s]	10		12.8

Table 3: Parameters values of transient thermal impedances in transformers with the big ring core RTP

orientation	horizontally		vertically	
parameter	$Z_{thW}(t)$	$Z_{thWC}(t)$	$Z_{thW}(t)$	$Z_{thWC}(t)$
R_{th} [K/W]	13.5	11.1	11.1	9.01
a_1	0.6	0.774	0.742	1
a_2	0.192	0.226	0.118	
a_3	0.148		0.09	
a_4	0.06		0.05	
τ_{th1} [s]	1062.5	1078.4	680.1	654.9
τ_{th2} [s]	470.5	459.4	114.8	
τ_{th3} [s]	30.9		19.4	
τ_{th4} [s]	5.64		14.7	

Table 4: Parameters values of transient thermal impedances in transformers with the small ring core RTF

parameter	$Z_{thW}(t)$	$Z_{thWC}(t)$	$Z_{thC}(t)$
R_{th} [K/W]	24.88	14.26	11.98
a_1	0.651	1	0.92
a_2	0.255		0.08
a_3	0.094		
τ_{th1} [s]	474.1	449.5	483.4
τ_{th2} [s]	126.8		53.1
τ_{th3} [s]	9		

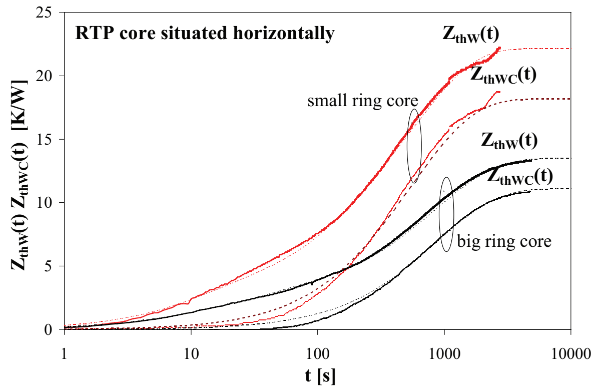
Table 5: Parameters values of transient thermal impedances in transformers with the big ring core RTF

orientation	horizontally		vertically	
parameter	$Z_{thW}(t)$	$Z_{thWC}(t)$	$Z_{thW}(t)$	$Z_{thWC}(t)$
R_{th} [K/W]	14	7.59	13.42	6
a_1	0.595	1	0.605	1
a_2	0.225		0.275	
a_3	0.13		0.118	
a_4	0.05		0.002	
τ_{th1} [s]	918	1050.5	792.8	800
τ_{th2} [s]	224.8		152.8	
τ_{th3} [s]	23.5		11.18	
τ_{th4} [s]	5.67		5.67	

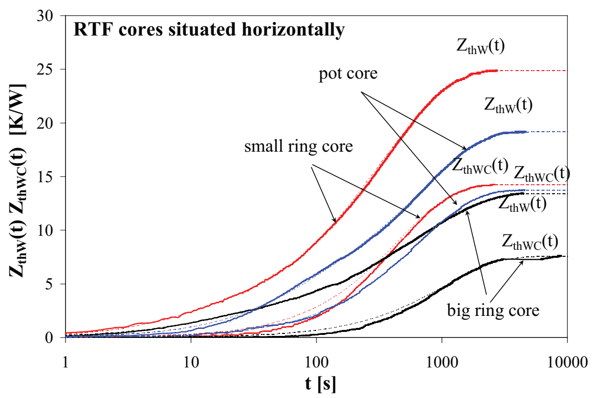
Comparing the data collected in the mentioned tables one can observe that the description of the considered transient thermal impedances demands the use of a different number of thermal time constants τ_{thi}. In the case of large ring cores RTP and RTF up to 4 thermal time constants appear in the description $Z_{thW}(t)$, while in the description $Z_{thWC}(t)$ for both ferrite cores RTF - just only one thermal time constant. In all the considered cases the prevailing meaning has the longest thermal time constant τ_{th1}. The corresponding to it weight- coefficient a_1 assumes the values in the range from 0.595 to 1. In turn, the values τ_{h1} are in the range from 471 s (for the small ring core RTF) to 1078 s for the large ring core RTP.

The presented below results of investigations illustrate the influence of geometrical dimensions of the core (Fig.6), its spatial orientation (Fig. 7), shape of the core (Fig. 8), current of the primary winding (Fig. 9), material the core is made of (Fig. 10) and frequency of the current on the primary winding (Fig. 7) on waveforms of the transformers' self and mutual transient thermal impedances.

In Fig. 6 the measured and modelled with the Eq. (3) waveforms of transient thermal impedance of the winding $Z_{thW}(t)$ and mutual transient thermal impedance between the winding and the core $Z_{thWC}(t)$ for transformers containing ring cores RTP (Fig.6a) or ring cores RTF (Fig. 6b) of different dimensions are presented. The measurements were performed at the stimulation of the primary winding with the direct current of the value equal to 9 A.



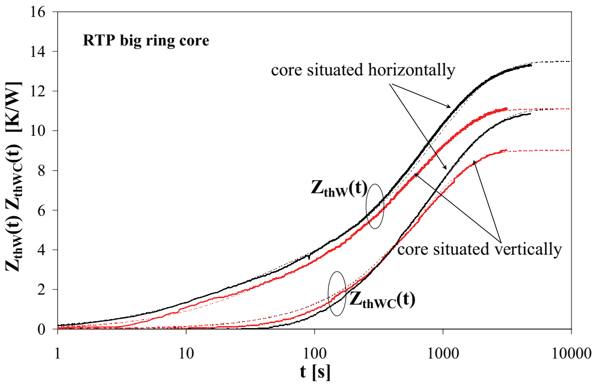
a)



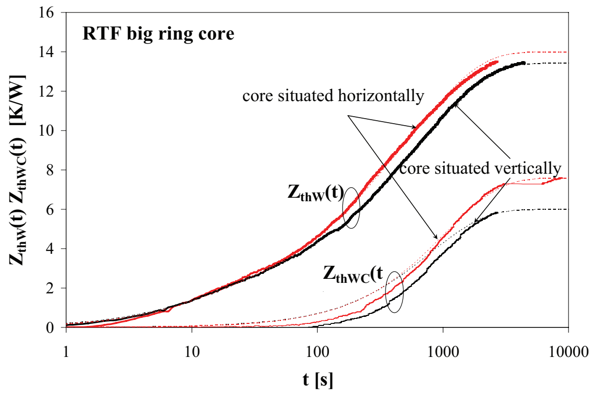
b)

Figure 6: Measured (solid lines) and modelled (dashed lines) waveforms of transient thermal impedances in transformers with ring cores RTP (and) and RTF (b) of different dimensions at the stimulation with the direct current of the primary winding and the horizontal orientation of the core

As one can notice in Fig. 6, the process of heating the core and the winding of the transformer with the considered cores runs slowly. The time indispensable to obtain the steady state exceeds 3000 s for the small ring core, 4000 s - for the pot core and 5000s - for the large ring core. The value of transient thermal impedances $Z_{thW}(t)$ is about 40% greater for the transformer with the small ring core RTP than for the transformer with the large ring core RTP (Fig. 6a). In the case of the transformer with the core RTF (Fig. 6a) one obtained greater by about 10% values of the considered parameter for transformers with ring cores made of the same material, while the transformer with the pot core shows average values of the time needed to settle the course between the values of this parameter corresponding to different measurements of ring cores. Waveforms of mutual transient thermal impedance between the winding and the core $Z_{thWC}(t)$ are late in relation to waveforms $Z_{thW}(t)$ by more than 20 s, and values $Z_{thWC}(t)$ at the steady-state are smaller than the value $Z_{thW}(t)$ at the steady-state. For transformers with cores RTP this difference is about 15%, and in the case of transformers with cores RTF these differences are bigger and are



a)



b)

Figure 7: Measured (solid lines) and modelled (dashed lines) waveforms of transient thermal impedances in the transformer with the core RTP (and) and RTF (b) at the stimulation with the direct current in the vertical and horizontal orientation of transformers

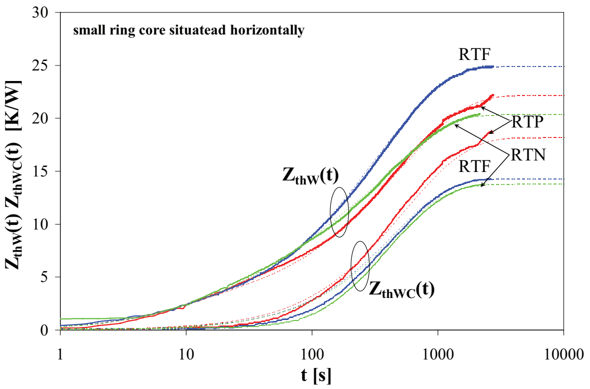
about 50% for ring cores and about 30% for the sot core. For all the considered waveforms the very good agreement between the results of measurements and the calculations performed with the use of the considered model is obtained.

In Fig. 7 waveforms $Z_{thW}(t)$ and $Z_{thWC}(t)$ for transformers with large ring cores RTP (Fig. 7a) and RTF (Fig.7b) placed both horizontally and vertically at the stimulation of the primary winding with the direct current of the value 9 A are presented.

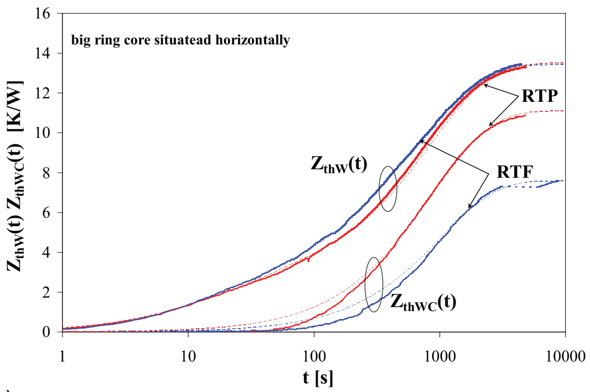
As one should expect the waveforms $Z_{thW}(t)$ and $Z_{thWC}(t)$ obtained in horizontal orientations lie above the waveforms obtained for the transformers situated vertically. It is the result of more efficient convection of heat for elements situated vertically, similarly to the situation with transistors mounted on any heat-sink situated vertically [9]. The vertical orientation of the considered elements quickens the perpendicular air flow along the sides of these elements, because the length of these sides is greater at this arrangement of the investigated element. The values of the considered transient thermal impedances in the steady-state in the horizontal and vertical orientation differ from each other by about 15% for the transformer with the core RTP and by about 10% for the transformer with the core RTF. It is visible that the considered model approximates well the measured waveforms $Z_{thW}(t)$, whereas it is possible to observe divergences between the measured and approximated waveforms $Z_{thWC}(t)$, especially for small values of time t.

In Fig.8 the influence of the selection of material of the ferromagnetic core on waveforms $Z_{thW}(t)$ and $Z_{thWC}(t)$ of transformers containing the small (Fig. 8a) or large (Fig. 8b) ring core is illustrated. The measurements were performed at the stimulation of the primary winding with the direct current of the value 9A.

As it can be noticed in Fig.8a, heat removal from the transformer containing the ferrite core (RTF) is the least efficient, while transformers with the powder core (RTP) and nanocrystalline core (RTN) have almost identical waveforms $Z_{thW}(t)$. It is worth noticing that dissipation of power of the same value in the winding causes a considerably higher temperature increase of the core RTP than the remaining cores, considered in this paper. This results from the greater value of thermal conductance of this material, which causes more efficient removal of heat generated in the winding through the core. Therefore, in the transformer with this core considerably smaller differences appear between temperatures of the winding and of the core than for the remaining considered transformers. The qualitatively similar results were obtained for transformers containing the large ring core. In this case, increases of the



a)



b)

Figure 8: Measured (solid lines) and modelled (dashed lines) waveforms of transient thermal impedances of transformers with the small (a) or large (b) ring core made of different materials

winding and the core temperatures of the transformer with the core RTP differ only just by about 20%, and for the transformer with the core RTF – up to about 60%.

In Fig. 9 the influence of the current flowing through the primary winding of the transformer on waveforms of transient thermal impedance of the winding and mutual thermal impedance between the winding and the core was illustrated. The measurements were performed for the transformer with the large ring core RTP situated horizontally for the current equal 7.35A and 9.1A, respectively.

As one can notice, with the current of the primary winding of the value 9.1A the values $Z_{thW}(t)$ and $Z_{thWC}(t)$ are by about 8% smaller than with the current equal to 7.35A. The improvement of efficiency of cooling with an increase of the current of the winding results from an increase in the value of the power dissipated in this element, which causes a temperature rise of the winding. In turn, the temperature rise of the winding causes an increase in efficiency of heat convection.

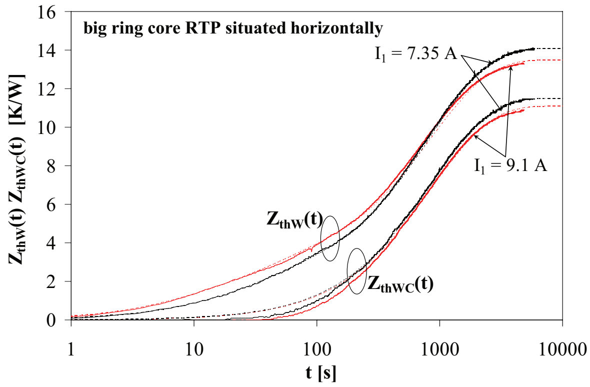


Figure 9: Measured (solid lines) and modelled (dashed lines) waveforms of transient thermal impedances of transformers with the large ring core RTP at the stimulation with the direct current of different values

Fig. 10 illustrates the influence of the shape of the waveforms $Z_{thC}(t)$ of the transformer with the core RTF at the stimulation of the primary winding with the sinusoidal signal. In this case the power dissipated in the winding is negligible in relation to the power dissipated in the core.

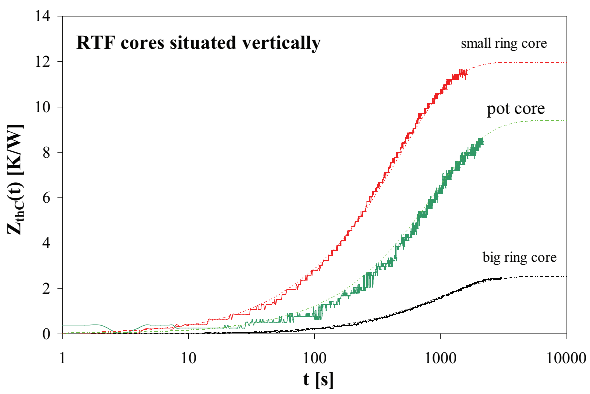


Figure 10: Measured (solid lines) and modelled (dashed lines) waveforms of transient thermal impedance of the core of transformers with the core RTF at the stimulation with the sinusoidal current

In Fig. 10 distinct differentiation of the obtained waveforms $Z_{thC}(t)$ is visible. The large ring core assures the most efficient cooling and the small ring core - the least efficient. The average values $Z_{thC}(t)$ are obtained for the transformer with the pot core. The obtained values of the considered transient thermal impedance differ from each other even four times.

In Fig. 11 the influence of frequency of the signal stimulating the primary winding of the transformer with the large ring core RTP on the waveforms $Z_{thC}(t)$ and $Z_{thCW}(t)$ is illustrated. Investigations were made for the transformer placed horizontally at two values of frequency equal to 25kHz and 75kHz, respectively. It is visible that an increase of frequency of the stimulating signal from 25 kHz to 75 kHz causes an increase in the value of transient thermal impedances Z_{thC}(t) and Z_{thCW}(t) by about 10%.

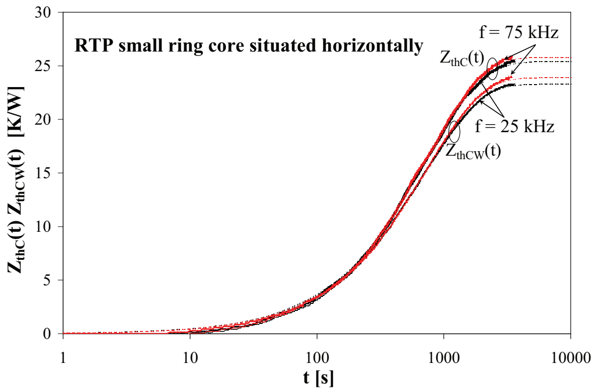


Figure 11: Measured (solid lines) and modelled (dashed lines) waveforms of transient thermal impedance of the core and mutual transient thermal impedance between the core and the winding of the transformer with the small ring core RTP at the stimulation with the sinusoidal current of frequency equal to 25kHz and 75kHz

The observed differences between waveforms of the considered thermal parameters can be caused not only by changes of the value of frequency, but also with changes of the power dissipated in the core at these frequencies (1 W at f = 25 kHz and 0.8 W at f = 75 kHz). Similarly, as this was shown in Figs. 9, an increase in the value of the power dissipated in the considered element causes a decrease in the value of thermal parameters of the transformer.

As one can notice in Figs. 6 - 11 for all the considered constructions of transformers and for all the considered cooling conditions the good agreement between the results of measurements and calculations performed with the use of Eq. (3) was obtained. However, as it is results among other things, from papers [16, 17] thermal resistance existing in this model is a decreasing function of the power dissipated in the modelled element. The decreasing dependence of thermal resistance on the dissipated power is a result of improved cooling of the transformer component with an increase in their temperature. As it is commonly known efficiency of convection and radiation increases with an increase in temperature of the heat source. Therefore, the dependence of thermal resistance on internal temperature of the heating source (the core or the winding) can be approximated with the function of the form:

$$R_{th} = R_{th0} + R_{th1} \cdot \exp\left(-\frac{T - T_0}{a_p}\right) \quad (13)$$

where T denotes temperature of the considered component of the transformer, whereas R_{th0}, R_{th1}, T_0 and a_p are the model parameters.

The correctness of the presented description was verified experimentally. For example, in Fig.12 calculated (lines) and measured (points) dependences of thermal resistance of the winding R_{thW} and mutual thermal resistance between the winding and the core R_{thWC} on the dissipated power in the winding of the transformer with the big ring RTP core are shown. Solid lines correspond to the transformer placed horizontally, and dashed lines - to the transformer situated vertically.

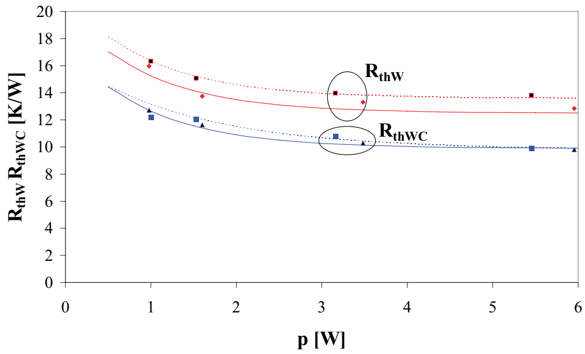


Figure 12: Measured (points) and modelled (lines) dependences of thermal resistance of the winding and mutual thermal resistance between the winding and the core on the dissipated power for the transformer with the big ring core RTP at the stimulation with the dc current

As it is visible, both the considered dependences are monotonically decreasing functions. The good agreement between the results of calculations and measurements is obtained. This proves that the proposed descriptions of the dependences R_{thW}(p) and R_{thWC}(p) are useful.

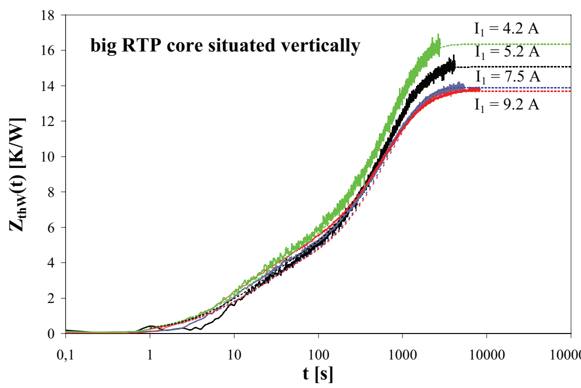


Figure 13: Measured (solid lines) and modelled (dashed lines) waveforms of self transient thermal impedance of the winding of the transformer with the big ring core RTP situated vertically at the stimulation with the direct current of different values

The considered dependences were used to model waveforms of transient thermal impedances of the impulse transformer. In this model only the value of thermal resistance is a function of the dissipated power given by Eq. (7), whereas the values of parameters a_i and τ_{thi} existing in Eq. (3) are constant for the considered transformer. For example, in Fig.13 the waveforms of measured (solid lines) and calculated (dashed lines) transient thermal impedance of the winding of the transformer with the big RTP core are presented at different values of the power dissipated in the primary winding. As it is visible, the good agreement between the results of calculations and measurements is obtained.

The difference between the temperature inside the core and on its surface is caused only by a non-zero value of thermal conductance of material used to make the core. Of course, the temperature inside the core is the highest, when power losses in the core dominate. In turn, the temperature rise of the core as a result of thermal coupling between this core and the windings is higher on the surface of the core than in the middle of it. Therefore, it is difficult to formulate the universal dependence between the temperature inside the core and on its surface. It is possible only to estimate the difference between temperatures of the surface and the middle of the core assuming that the only mechanism of heat transfer is conduction, generation of heat appears in the infinitely thin ring situated in the middle of the core, and heat flux density has uniform distribution. With these assumptions, for the ring core of the outside diameter equal to 5 cm, the inside diameter equal to 3 cm and the height equal to 1 cm, made of powdered iron at the power dissipated in the core of the value equal to 1 W the maximum temperature difference between the middle of the core and its surface amounts to 14 K.

5 Conclusions

In the paper the method to measure transient thermal impedances in the transformer and the results of measurements, illustrating the influence of the selected factors on waveforms of these thermal parameters, are presented. The research done by the Authors proves that efficiency of cooling the structural components of the transformer can be characterised by means of parameters of the compact thermal model and that the waveforms of the considered thermal parameters change depending on many factors.

For example, an increase in the value of the power dissipated in the winding by more than 30% causes a decrease of the waveforms $Z_{thW}(t)$ by several percent. In turn, enlargement of the diameter of the ring core by about 60% is effective with deterioration of thermal resistance by even about 50% and with extension of the indispensable time to obtain the steady state even by about 60%. For comparatively large sizes of the investigated elements, the time indispensable to obtain the thermally steady state reaches even 2 hours. The change of spatial orientation of the transformer (horizontal or vertical orientation) causes a change of the considered parameters by even about 20%.

The essential meaning has also the material, the core is made of, because its thermal conductance influences the measured waveforms $Z_{thW}(t)$ and $Z_{thWC}(t)$ in an essential manner. The least differences between waveforms of the mentioned thermal parameters, not exceeding 20%, were observed for transformers with cores RTP (characterised by high thermal conductance), and the greatest (by even above 50%) - for cores RTF.

The analytic description of dependences of self and mutual thermal resistances of the transformer on the power dissipated in it is proposed. It was shown experimentally that the use of this dependence in the classical literature model of transient thermal impedance assured correct modelling of waveforms of transient thermal impedances of the transformer over a wide range changes of the current of the primary winding.

It is worth noticing that the classical literature description of transient thermal impedance with the proposed description of thermal resistance enables very good approximation of the measured waveforms of transient thermal impedance of the winding for all the considered transformers. One observes, however, essential differences between the measured and approximated waveforms of mutual transient thermal impedances between the winding and the core and transient thermal impedances of the core for transformers containing ferrite or nanocrystalline cores. In the mentioned above transformers a large delay of the process of heating the core appears, which reaches even 100 s. The correct modelling of this delay demands correction in the thermal model of the transformer, which is at present an objective of the Authors investigations.

The results of investigations presented in this paper can be useful for constructors of impulse-transformers and constructors of switched-mode power supplies containing these transformers. These results will be of service also to the Authors as experimental material, indispensable to formulate the non-linear electro-thermal model of the impulse-transformer. In this model the influence of internal temperature of the core and the windings, of dimensions of the core and its spatial orientation on thermal parameters of the transformer will take into account.

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