The influence of core material on transient thermal impedances in transformers

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Abstract. In the paper the results of measurements of thermal parameters of impulse-transformers containing cores made of different ferromagnetic materials are presented. Investigations were performed with the use of methods worked out in Gdynia Maritime University. The obtained results of measurements prove that the material of the core does not influence transient thermal impedance of the winding, whereas this parameter visibly changes with the change of spatial orientation of the transformer. In turn, the material of the core decides about transient thermal impedance of the core. Additionally, the influence of the core material on temperature distribution on the surface of the transformer was analysed.

1. Introduction

Impulse-transformers are commonly used in switch-mode power supplies [1, 2, 3]. The considered elements have a simple construction - they consist of the ferromagnetic core and windings. The properties of both these components depend on temperature, whose change causes changes in the value of exploitive parameters of the core and windings [4, 5, 6]. Particularly, if the core temperature is higher than the Curie temperature, permeability of this core decreases to 1, and when the windings temperature is higher than its admissible value, isolation of wires can be destructed [1, 2].

The temperature of the core and windings of the transformer during its operation is higher than the ambient temperature due to self-heating phenomena in the core and in the windings, as well as the mutual thermal coupling between these components of the transformer [4, 7, 8, 9]. In the papers [4, 8, 9] compact thermal models of the transformer are proposed. These models use the idea of the transformer's own and mutual transient thermal impedances well-known from models of semiconductor devices [10, 11, 12]. As it is known from some papers, e.g. [11, 13], thermal parameters of semiconductor devices depend on such factors as dissipated power, dimensions of the considered devices and construction of the cooling system. Therefore, it can be expected that thermal parameters of transformers depend on their dimensions and parameters of materials used to produce ferromagnetic cores. Magnetic materials are characterized by different values of thermal conductance, which should influence transient thermal impedance of the transformer.

In the paper the results of measurements of transformers' own and mutual transient thermal impedances, obtained with the use of the measurement method elaborated at Gdynia Maritime University [14], are presented. These transformers contain cores made of different materials. Additionally, inequalities of temperature distribution on the surface of the investigated elements are discussed.

2. Measurement methods

In the research the method of measurements of the transformer's own and mutual transient thermal impedances described in the paper [14] is used. This method is realised in the measurement set presented in Figure 1.

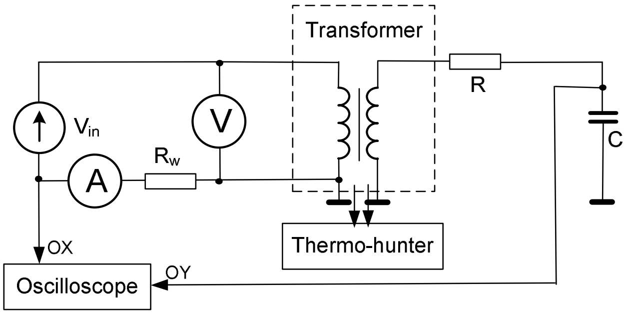

Figure 1. The measurement set to measure thermal parameters of transformers [14]

The measurements are conducted in two steps. The first step needs stimulations of the primary winding with a jump of the current and the measurement of temperature changes of windings and of the core by means of the thermo-hunter until the thermally steady-state is obtained. These measurements are used to calculate transient thermal impedance of the winding $Z_{thU}(t)$ and mutual transient thermal impedance between the core and the windings $Z_{thUR}(t)$ using the following formulas:

$$Z_{thU}(t) = \frac{T_U(t) - T_a}{P} \tag{1}$$

$$Z_{thUR}(t) = \frac{T_R(t) - T_a}{P} \tag{2}$$

where $T_U(t)$ and $T_R(t)$ denote waveforms of the winding and core temperatures, respectively, T_a is the ambient temperature, whereas P denotes power dissipated in the winding, which is equal to the product of the winding current and the voltage on the primary winding.

In the second step, the primary winding of the transformer is stimulated by a sinusoidal signal of frequency f and the temperature of the core is measured by the thermo-hunter. When the steady state is obtained, in the moment $t = 0$ the power supply of the primary winding is switched off and waveforms of temperature of the core and windings are measured. On the basis of the area S_H of the obtained hysteresis loop $B(H)$ of the core and the measured waveform of the core temperature, transient thermal impedance of the core $Z_{thR}(t)$ is calculated using the following formula

$$Z_{thR}(t) = \frac{T_R(t=0) - T_R(t)}{V_R \cdot f \cdot S_H} \tag{3}$$

where V_R represents the volume of the core.

The detailed description of the method is included in [14].

3. Measurement results

Using the method presented in section 2, the measurements of thermal parameters of transformers containing toroidal cores of the diameter equal to about 26 mm are performed. The core made of powdered iron (RTP), the ferrite core (RTF) and the nanocrystaline core (RTN) are applied. Each of the considered transformers has two windings made of 30 turns of copper wire in enamel of the diameter equal to 0.8 mm.

In the further part of this section the results of measurements illustrating the influence of core material and spatial orientation of the transformer on the courses of transient thermal impedances $Z_{thU}(t)$, $Z_{thR}(t)$ and $Z_{thUR}(t)$ are presented. The spectrum of transient thermal impedances for all the considered cooling conditions and selected temperature distributions on the surface of the investigated transformers are also shown. All the measurements are performed at the constant ambient temperature equal to 22°C. In all the figures presented in this section, solid lines correspond to the transformer situated horizontally, and dashed lines - the transformer situated vertically. With the red colour the measured courses of $Z_{thU}(t)$ are marked, with the blue colour - courses $Z_{thR}(t)$, and with the black colour - courses $Z_{thUR}(t)$.

The spectrum of transient thermal impedances illustrates the values of parameters describing waveforms of $Z_{th}(t)$ by means of the classical analytic formula [10, 12, 15]

$$Z_{th}(t) = R_{th} \cdot \left[1 - \sum_{i=1}^{N} a_i \cdot \exp\left(-\frac{t}{\tau_{thi}}\right)\right] \tag{4}$$

where R_{th} denotes thermal resistance, N – number of thermal time constants τ_{thi} corresponding to coefficients a_i.

In Figure 2a the measured waveforms of transient thermal impedances $Z_{thU}(t)$, $Z_{thUR}(t)$ and $Z_{thR}(t)$ for the transformer containing the nanocrystaline core are presented, whereas in Figure 2b – the spectrum of thermal time constants of this transformer is shown. Parameters values of the thermal model of the considered transformer are collected in Table 1.

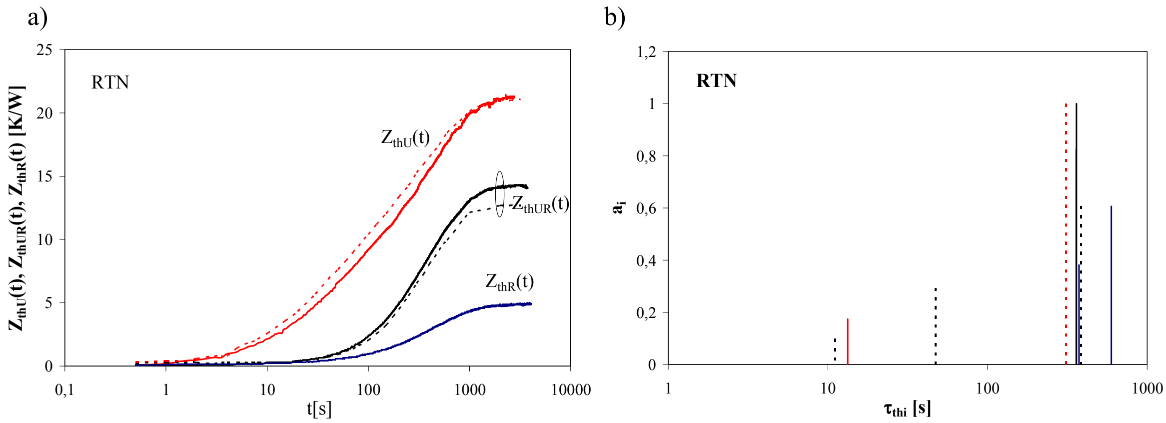

Figure 2. Transient thermal impedances in the transformer with the RTN core (a) and the spectrum of thermal time constants of this transformer(b)

Table 1. Parameters values of the thermal model of the transformer with the RTN core.

parameter	transformer situated horizontally			transformer situated vertically	
	$Z_{thU}(t)$	$Z_{thUR}(t)$	$Z_{thR}(t)$	$Z_{thU}(t)$	$Z_{thUR}(t)$
R_{th} [K/W]	20.94	14.1	4.91	21.02	12.56
a_1	0.826	1	0.606	0.608	1
a_2	0.174		0.382	0.294	
a_3			0.012	0.098	
τ_{th1} [s]	359.1	361.7	597.9	385.4	310.1
τ_{th2} [s]	13.35		373.6	47.3	
τ_{th3} [ms]			40	98	

As one can notice in Figure 2a, the process of heating the core and winding of the transformer runs slowly. The indispensable time to obtain the steady state exceeds 3000 s. It is worth paying attention to the fact that the process of heating the winding runs more quickly, and the courses $Z_{thUR}(t)$ and $Z_{thR}(t)$ are late with regard to the course $Z_{thU}(t)$ by even about 100 s. Additionally, it is visible that the steady-state values of transient thermal impedance of the winding are even about 20% higher than the values of transient thermal impedance between the winding and the core of this transformer. On the other hand, the values of transient thermal impedance of the core are even four times smaller than $Z_{thU}(t)$. The influence of orientation of the transformer in the vertical-line or in the horizontal-line on the course of transient thermal impedance is visible only in the case of $Z_{thUR}(t)$, where the value of this parameter at the steady-state at vertical orientation is about 10% lower than at horizontal orientation of this element.

In Figure 2b it is visible that the presented in Figure 2a waveforms of transient thermal impedances can be described with the use of 1 to 3 thermal time constants, whereas the prevailing thermal time constant accepts values in the range from 200 to 300 s. Orientation of the transformer does not influence in an essential manner the value of thermal time constants.

In Figure 3 distribution of temperature on the surface of the investigated transformer with the RTN core, obtained at the steady-state at different conditions of power supply of this transformer, are shown. At dc stimulation the current of the primary winding is equal to about 9 A, whereas at the stimulation of the primary winding with the sinusoidal current the amplitude is 2.4 A and frequency 5.5 kHz.

As one can notice for the transformer with the RTN core, at the stimulation with the direct current, temperature on its surface at horizontal orientation accepts the values in the range from 40°C to 78°C, at vertical orientation - the values of temperature from 40°C to 71°C, and at the stimulation of the transformer with the sinusoidal current, temperature on its surface at horizontal orientation has the values in the range from 30°C to 42°C. It should be noted that visible differences between the temperature of the core and winding occur. At the power supply with the direct current the winding has higher temperature, and at the power supply with the sinusoidal current - the core. Warmer areas of the windings show the visible difference of temperatures not higher than several Celsius degrees, similarly to the values of temperature on the surface of the core.

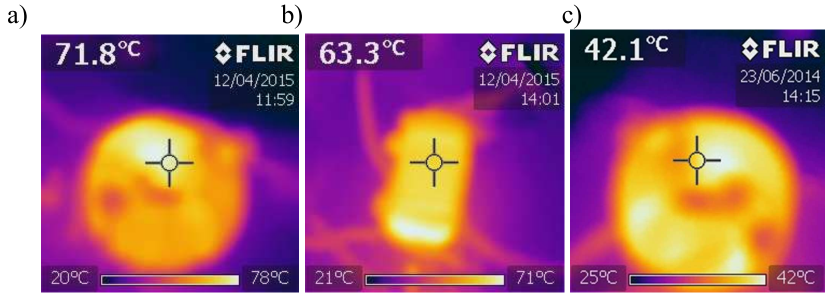

Figure 3. Temperature distribution on the surface of the transformer with the RTN core at the stimulation by: a) the dc current at horizontally situated transformer, b) the dc current at the vertically situated transformer, c) the sinusoidal waveform of the current at the horizontally situated transformer

In Figure 4a the measured waveforms of transient thermal impedances $Z_{thU}(t)$, $Z_{thUR}(t)$ and $Z_{thR}(t)$ for the transformer containing the powder core (RTP) are presented, whereas in Figure 4b – the spectrum of thermal time constants of this transformer is shown. Parameters values of the thermal model of the considered transformer are collected in Table 2.

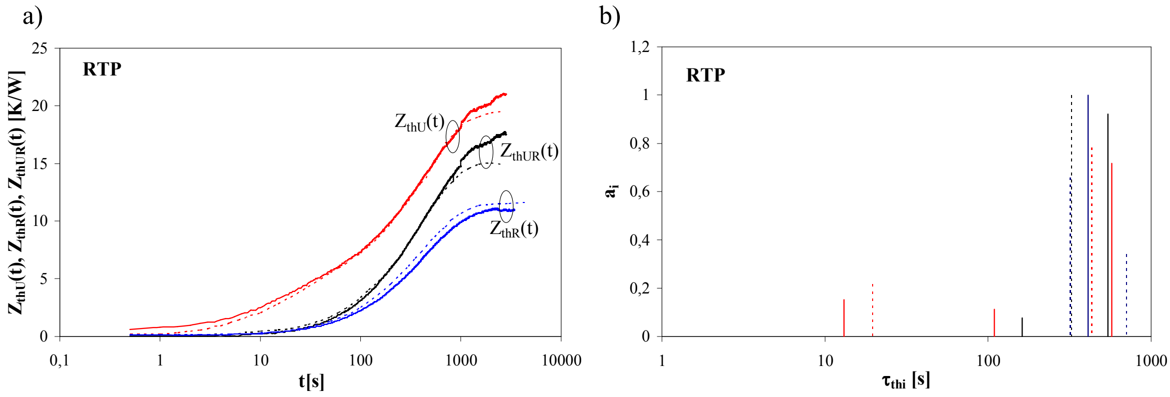

Figure 4. Transient thermal impedances in the transformer with the RTP core (a) and the spectrum of thermal time constants of this transformer(b)

Table 2. Parameters values of the thermal model of the transformer with the RTP core.

parameter	**transformer situated horizontally**			**transformer situated vertically**		
	$\mathbf{Z_{thU}(t)}$	$\mathbf{Z_{thUR}(t)}$	$\mathbf{Z_{thR}(t)}$	$\mathbf{Z_{thU}(t)}$	$\mathbf{Z_{thUR}(t)}$	$\mathbf{Z_{thR}(t)}$
R_{th} [K/W]	20.98	17.62	10.94	19.36	14.82	11.69
a_1	0.717	0.922	1	0.784	1	0.341
a_2	0.113	0.078		0.216		0.659
a_3	0.153					
a_4	0.017					
τ_{th1} [s]	572.8	541.9	410.2	433.2	325.9	708.6
τ_{th2} [s]	109.3	161.9		19.57		320
τ_{th3} [s]	13.06					
τ_{th4} [ms]	40					

As one can notice in Figure 4a the process of heating the core and the winding of the transformer with the RTP core occurs similarly as for the transformer with the RTN core. The time indispensable to obtain the steady state exceeds 3000 s. The obtained value $Z_{thU}(t)$ at the steady-state amounts to about 22 K/W and it is practically the same as for the transformer with the RTN core, whereas values $Z_{thUR}(t)$ and $Z_{thR}(t)$ for the transformer with the RTP core are considerably (even twice) higher than for the transformer with the RTN core. At vertical orientation smaller by about 10 - 20 % values of $Z_{thU}(t)$ and $Z_{thUR}(t)$ than for horizontal orientation of this transformer are obtained. In turn, the influence of orientation of the transformer on the course $Z_{thR}(t)$ is omittably weak.

In Figure 4b it is visible that the presented in Figure 4a waveforms of transient thermal impedances can be described with the use from 1 to 3 thermal time constants, whereas the prevailing thermal time constant accepts values in the range from 200 to 500 s. It is visible that at vertical orientation of the transformer deterioration of the prevailing thermal time constant by even about 50% is observed.

In Figure 5 distribution of temperature on the surface of the investigated transformer with the RTP core obtained at the steady state at different conditions of stimulation of this transformer are shown. At dc stimulation the current of the primary winding is equal to about 9 A, whereas at the stimulation of the primary winding with the sinusoidal current the amplitude is 2.4 A and frequency 5.5 kHz.

a) b) c) d)

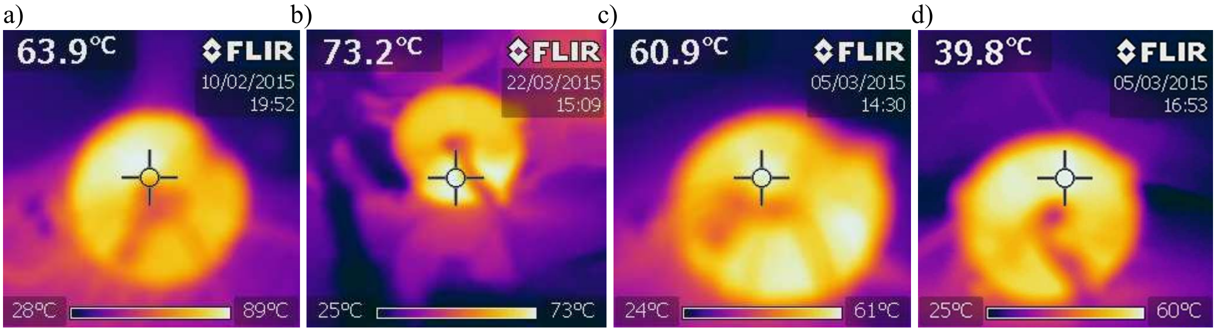

Figure 5. The temperature distribution on the surface of the transformer with the RTP core at the stimulation by: a) the dc current at the horizontally situated transformer, b) the dc current at the vertically situated transformer, c) the sinusoidal waveform of the current at the horizontally situated transformer, d) the sinusoidal waveform of the current at the vertically situated transformer

As one can notice for the transformer with the RTP core, at the stimulation with the direct current, temperature on its surface at horizontal orientation accepts values in the range from 40°C to 89°C, at vertical orientation - values of temperature in the range from 40°C to 73°C. In turn, at the stimulation of the transformer with the sinusoidal current, temperature on its surface at vertical and horizontal orientation accepts values of temperature in the range from 40°C to 61°C.

It is proper to notice that visible differences between the temperature of the core and the winding appear. However, warmer areas of windings show not big differentiation in temperature, not exceeding several Celsius degrees, similarly to values of temperature on the surface of the core.

The measurements of temperature distribution on the surface of the transformer and the courses of transient thermal impedances are performed also for transformers containing the ferrite core (RTF). The results of such measurements are shown in Figure 6 for the transformer situated horizontally. As it is visible, the obtained results qualitatively agree with the presented above results of measurements of transformers with the RTP and RTN cores. Parameters values of the thermal model of the transformer with the RTF core are collected in Table 3.

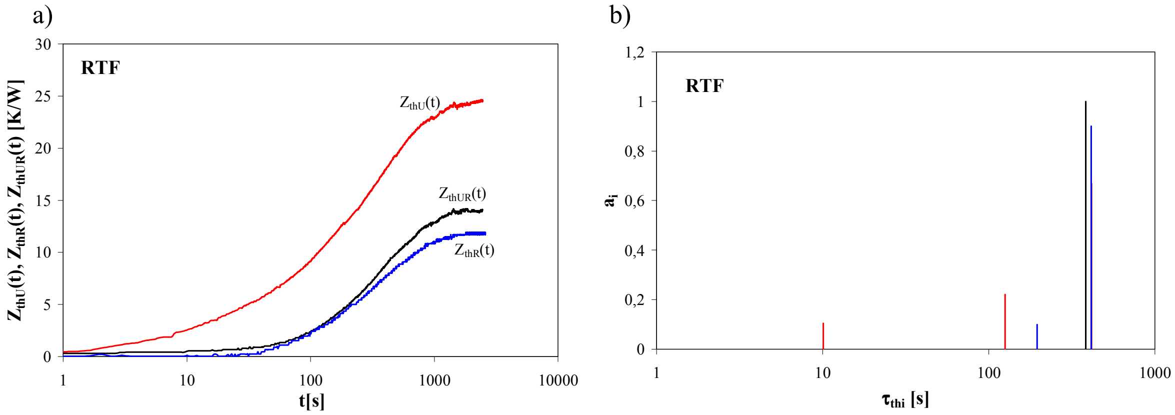

Figure 6. Transient thermal impedances in the transformer with the RTF core (a) and the spectrum of thermal time constants of this transformer(b)

Table 3. Parameters values of the thermal model of the transformer with the RTF core situated horizontally.

parameter	**transformer situated horizontally**		
	$Z_{thU}(t)$	$Z_{thUR}(t)$	$Z_{thR}(t)$
R_{th} [K/W]	24.55	14	11.9
a_1	0.669	1	0.9
a_2	0.221		0.1
a_3	0.105		
a_4	0.005		
τ_{th1} [s]	415.8	384.35	413.6
τ_{th2} [s]	125.1		195.4
τ_{th3} [s]	10.1		
τ_{th4} [ms]	40		

The obtained values of thermal resistance of the winding is equal to about 25 K/W, the mutual thermal resistance between the winding and the core is equal to about 14 K/W and thermal resistance of the core is equal to about 12 K/W. Thermal time constants accept values in the range from 10 s to about 400 s. Therefore, time indispensable to obtain the steady state is shorter than for the other considered transformers.

The temperature distribution on the surface of considered transformer are also measured and the obtained results are similar to temperature distributions presented in Figure 5 for the RTP core.

4. Conclusions

In the paper the results of measurements of transformers' own and mutual transient thermal impedances in transformers containing cores made of different materials and temperature distribution on the surface of these elements at the steady-state are presented. From the obtained results of measurements it results that the material of the core has a visible influence on the waveforms of transient thermal impedances of the core included in the transformer, but it influences transient thermal impedance of the winding in an omittably weak way. The highest value of this transient thermal impedance is the highest for the transformer with the RTF core. Differences in the waveforms of transient thermal impedance of the core can be a result of thermal conductance of the core material. The highest values of the transient thermal impedance of the core is obtained for transformer with the RTF core. In the steady state its value is even twice higher than the value of this parameter for the transformer with the RTN core. On the other hand, the influence of transformers orientation on their transient thermal impedances for the transformer situated vertically is visible, and typically smaller values of these parameters are obtained.

The obtained distribution of the surface temperature of the transformer shows that inequality of distribution of temperature in the examined transformers does not exceed a dozen or so kelvins. This justifies the use of compact thermal models in the description of thermal properties of the examined transformers.

5. References

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