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Modelling thermal properties of planar transformers

Streszczenie. *W pracy zaproponowano model termiczny transformatora planarnego umożliwiający wyznaczenie temperatury rdzenia oraz każdego uzwojenia. Model ten uwzględnia samonagrzewanie i wzajemne sprzężenia cieplne między komponentami transformatora. Uwzględniono zależność rezystancji termicznych od mocy wydzielanej w transformatorze. Poprawność modelu zweryfikowano doświadczalnie. (**Modelowanie właściwości cieplnych transformatorów planarnych**).*

***Abstract**. In the paper the thermal model of the planar transformer making possible calculations of the core and each winding temperature is proposed. This model takes into account self-heating and mutual thermal coupling between components of the transformer. The dependence of thermal resistances existing in this model on the power dissipated in the transformer is taken into account. The correctness of the model is verified experimentally.*

Słowa kluczowe: transformatory planarne, parametry cieplne, pomiary.
Keywords: Planar transformers, thermal parameters, measurements.

Introduction

Transformers are commonly used in electronic and power electronic circuits. The tendency to miniaturise these circuits, observed for many years, caused the need to diminish geometrical sizes of transformers. A simultaneous increase of switching frequency of these circuits allows reducing the number of turns of each winding of the transformer. This is the case for planar transformers, in which the winding has the form of paths on the printed circuit board (PCB), and the ferrite core surrounds this PCB.

Ii is observed in transformers, similarly as in other electronic components, that thermal phenomena (self-warming and mutual thermal couplings) cause a rise of their internal temperature. This increase can be considerable and can result in essential shortening of life-time of these elements and the change of the course of their characteristics [4]. In order to assure operating of the transformer in safe conditions and to limit temperature of this electronic component it is indispensable to take into account thermal phenomena. Therefore the thermal model of this device is necessary.

In the literature the problem of modelling thermal phenomena in planar transformers is discussed. For example, in the paper [5] the use of the finite element method to mark the schedule of temperature in such an element is proposed. However, in calculations uniform distribution of power density in the modelled transformer is accepted. A result of this simplification is uniform distribution of temperature in the core.

In turn, in the paper [6] the problem of characterisation of the planar transformer is considered. In the cited paper the static compact thermal model of the planar transformer is proposed. Unfortunately, in the considered model only the power lost in windings of the transformer is taken into account, and losses in the core are skipped.

In the paper [7] the compact thermal model of the transformer is proposed, where thermal proprieties of this element are characterised by self transient thermal impedances of the core and windings and mutual transient thermal impedances between the core and windings and between windings of the transformer. However, verification of correctness of this model was performed only for classical transformers with the ring core and the winding made of copper wire in the enamel.

As it was shown in the paper [8], for the transformer with the ring core strong dependence of the mentioned transient thermal impedances on construction of the considered transformer and the applied constructional materials are observed.

In the paper [9] the results of measurements of thermal parameters of the selected planar transformer operating at stimulation of the primary winding with the direct current are presented. In this paper the non-linear static thermal model of the planar transformer taking into account the influence of the power lost in the winding and in the core and the influence of construction of the transformer on parameters describing thermal proprieties of this element is proposed.

Model form

The presented thermal model of the transformer belongs to a group of compact thermal models, in which uniform distribution of temperature in its structural components is accepted. This model describes dependences of temperatures of the core T_C, of the primary winding T_{W1} and of the secondary winding T_{W2} on the power dissipated in these components of the transformer. At the steady-state these temperatures can be described as follows:

(1) $$T_C = R_{thC} \cdot p_C + R_{thCW1} \cdot p_{W1} + R_{thCW2} \cdot p_{W2}$$

(2) $$T_{W1} = R_{thW1} \cdot p_{W1} + R_{thCW1} \cdot p_C + R_{thWW} \cdot p_{W2}$$

(3) $$T_{W2} = R_{thW2} \cdot p_{W2} + R_{thCW2} \cdot p_C + R_{thWW} \cdot p_{W1}$$

where p_C, p_{W1} and p_{W2} denote powers dissipated in the core and in the primary and secondary windings of the transformer, R_{thC}, R_{thW1} and R_{thW2} - thermal resistances of the core and each winding, while R_{thCW1}, R_{thW2} and R_{thWW} - mutual thermal resistances between the core and each winding and mutual thermal resistance between the windings.

The method of measuring the mentioned thermal resistances is described in Section 4. However, the results shown in the paper [9] prove that the considered thermal resistances depend, among others, on the power lost in the winding and on spatial orientation of the transformer. This dependence can be described with the equation of the form

(4) $$R_{thW1} = R_{thW0} \cdot \left[1 + a \cdot \exp\left(-p_W/b\right)\right] \cdot w$$

where R_{thW0} denotes the minimum value of thermal resistance of the winding, w is the coefficient, whose value depends on spatial orientation of the transformer, while a and b are the remaining parameters of the model. The remaining thermal resistances occurring in the thermal model of the transformer are described with the equations of the form given by the formula (4), but the values of the parameters occurring in this formula are different for each thermal resistance.

Investigated transformers

The elaborated model was verified for the transformer containing the ferrite planar core E22/6/16R made of the material 3F3. The view of the mounted transformer is shown in Fig.1.

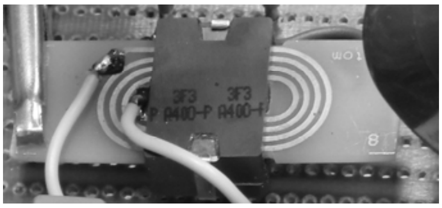


Fig. 1. View of the investigated transformer

The windings of transformers have the form of printed copper paths - 35 μm thick on the epoxy-glass laminate FR-4 of the thickness equal to 1 mm. The primary winding contains 3 spiral turns of the width 2.5 mm, whereas the secondary winding - 5 turns of the width 1 mm.

Measurement method of model parameters

Thermal proprieties of transformers describe self thermal resistances of the windings R_{thW1} and of the core R_{thC} and mutual thermal resistances: between the winding and the core R_{thW1C} and between the windings R_{thWW}. The mentioned thermal parameters can be measured in the measuring set-up shown in Fig. 2.

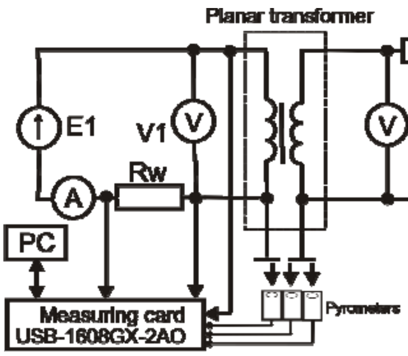


Fig.2. Set-up to measure thermal parameters of transformers while heating the primary winding

This set-up contains, except the investigated transformer, the source of feeding E1, the resistor Rw limiting the current of the primary winding, 3 pyrometers measuring temperatures of both the windings and the core of the transformer, the measuring-card, the controlling computer (PC), the volt-meter, the ammeter and the resistor R determining load of the secondary winding. The applied measuring-card by the firm Measurement Computing of the type USB-1608GX-2AO makes possible simultaneous measurements of voltage in 8 points at the maximum sampling rate equal to about 1 MHz. By means of this card it is possible to register the temporary values of temperatures of the core of $T_C(t)$, the primary winding of $T_{W1}(t)$ and the secondary winding $T_{W2}(t)$ obtained on the outputs of pyrometers of the type Optex PT-3S, and also the values of voltage on the primary winding $V_1(t)$ and the current of this winding $i_1(t)$.

The measurement is performed in two steps. In the first step of the measurement the primary winding is excited by the direct current of the value I_1. Having obtained the thermally steady state, the value of voltage V_1 on the primary winding of the transformer, the current of this winding I_1, temperature of the primary winding T_{W1}, temperature of the secondary winding T_{W2} and temperature of the core T_C are measured. In the second step, on the basis of the measured courses of temperatures of structural components of the transformer the values of thermal resistances of the winding R_{thW1}, mutual thermal reasistance between the winding and the core R_{thW1C} and mutual thermal resistance between windings R_{thWW} with the use of the below mentioned definitional formulas are calculated

$$R_{thW1} = \frac{T_{W1} - T_a}{V_1 \cdot I_1} \quad (5)$$

$$R_{thW1C} = \frac{T_C - T_a}{V_1 \cdot I_1} \quad (6)$$

$$R_{thWW} = \frac{T_{W2} - T_a}{V_1 \cdot I_1} \quad (7)$$

where T_a denotes the ambient temperature.

In Fig. 3 the set-up to measure thermal parameters of the planar core at stimulation of the core with the source of the direct currect is shown. This set-up, except the transformer with the planar core, contains the voltage source E2, the resistor Rw limiting the current, pyrometers measuring temperature of the core T_C and windings T_{W1} and T_{W2}, the measuring-card and the computer PC with software. To side-surfaces of the core on all of their length points of feeding connectors are joined.

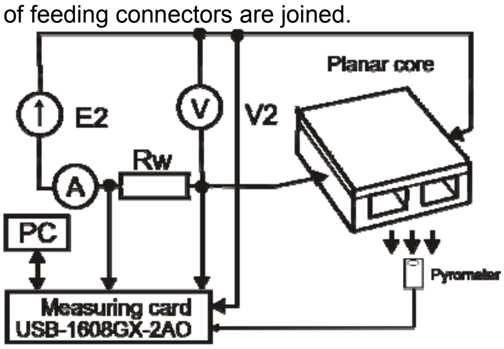


Fig. 3. Set-up to measure thermal parameters of the core while heating this core

The measurement is performed in two steps. In the first step of the measurement the core is excited by the direct current of the value I_2. Hence, until the thermally steady state is obtained temperatures of the core T_C and temperatures of windings T_{W1} and T_{W2} are measured. After the thermally steady state is obtained, the value of voltage V_2 and current I_2 flowing through the core are measured. Basing on the measured values of temperatures T_C, T_{W1} and T_{W2} thermal resistance of the core R_{thC} and mutual thermal resistance between the core and windings R_{thCW1} and R_{thCW2} with the use of below mentioned formulas are calculated

$$R_{thC} = \frac{T_C - T_a}{V_2 \cdot I_2} \quad (8)$$

$$R_{thCW1} = \frac{T_{W1} - T_a}{V_2 \cdot I_2} \quad (9)$$

$$R_{thCW2} = \frac{T_{W2} - T_a}{V_2 \cdot I_2} \quad (10)$$

Results

For the transformer, described in Section 3, calculations and measurements of the dependence of thermal resistance of the core, the windings and mutual thermal resistance between the core and the windings and between the windings on the dissipated power are performed. The selected results of these investigations are shown in Figs. 4-7.

In these figures the points denote the results of measurements, the lines – the results of calculations by means of the proposed model, whereas the solid lines refer to the transformer placed horizontally, and the dashed lines – to the transformer placed vertically.

Fig. 4 presents the measured dependences $R_{thW1}(p_{W1})$, $R_{thWC1}(p_{W1})$ and $R_{thWC2}(p_{W1})$ obtained at horizontal and vertical orientation of the investigated transformer and when only wires feeding the primary winding are connected to them. In turn, Fig. 5 shows the dependence $R_{thC}(p_C)$ obtained at horizontal orientation of the investigated transformer and when only wires feeding the core of the transformer are connected to them.

As it is visible, in all the cases, a good agreement between the results of calculations and measurements is obtained. All the considered dependences of thermal resistances on the power dissipated in the primary winding (Fig. 4) or in the core (Fig. 5) are monotonically decreasing functions, and the values of thermal resistance for the transformer situated vertically are even about 10% smaller than the value of this parameter for the transformer placed horizontally.

It is worth noticing that in the considered range of changes of the power dissipated in the primary winding p_{W1} the values of thermal resistances R_{thW1}, R_{thWW} and R_{thW1C} change only about 15%. In turn, the observed changes of the value R_{thC} exceed 30%.

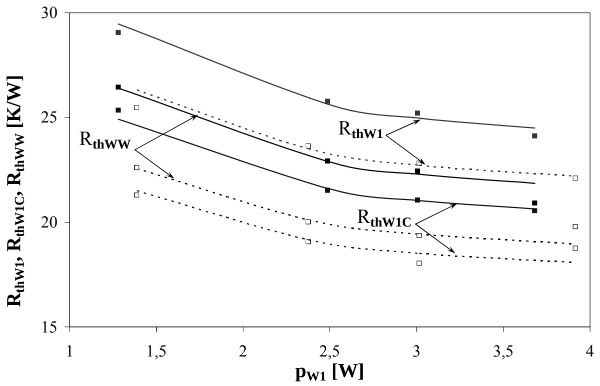


Fig. 4. Measured and calculated dependences of thermal resistance of the primary winding R_{thW1} and mutual thermal resistance between the winding and the core R_{thWC}, mutual thermal resistance between the windings R_{thWW} on the power in the primary winding p_{W1}

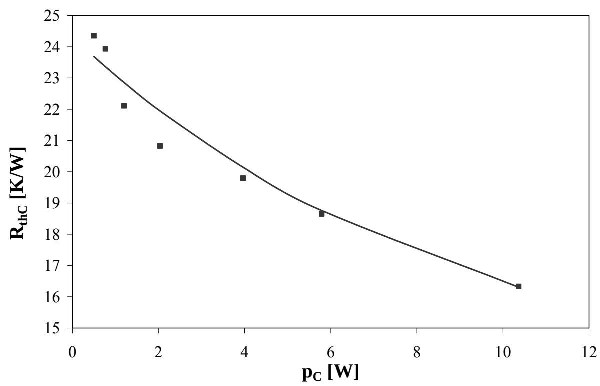


Fig. 5. Measured dependneces of thermal resistance of the core R_{thC} on power dissipated in the core p_C

The values of parameters existing in the formula (1) and describing dependences of the considered thermal resistances on the powers p_{W1} and p_C are assembled in Table 1 for the transformer placed horizontally.

Figs. 6 - 7 present the measured and calculated by means of the example (4) dependences of self and mutual thermal resistances occurring in the model of the transformer on the power p_{W1} dissipated in the winding (Figs. 6) and on the power p_C dissipated in the core (Figs. 7). The values of parameters describing the presented dependences are assembled in Table 2.

Table 1. Values of parameters describing dependences of thermal resistances on dissipated power for the transformer situated horizontally

parameter	R_{thW0} [K/W]	a	b [W]	w
R_{thW1}	24	0.82	1	1
R_{thWW}	20.2	0.84	1	1
R_{thWC}	21.4	0.84	1	1
R_{thC}	12.6	0.93	9	1

Table 2. Values of parameters describing dependences of thermal resistances on dissipated power in the components of transformer

parameter	R_{thW0} [K/W]	a	b [W]	w
R_{thW1}	25.5	0.5	2	1
R_{thWW}	19.4	0.55	2.2	1
R_{thWC}	13	0.45	1.8	1
R_{thC}	18.5	0.4	3.3	1
R_{thCW1}	12.6	0.55	2.7	1
R_{thCW2}	11.2	0.45	1.8	1

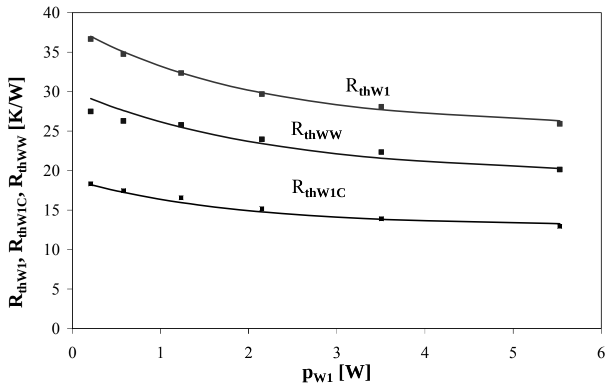


Fig. 6. Measured dependences of thermal resistance of the primary winding R_{thW1}, mutual thermal resistance between the winding and the core R_{thWC}, mutual thermal resistance between the windings R_{thWW} on the power dissipated in the primary winding p_{W1}

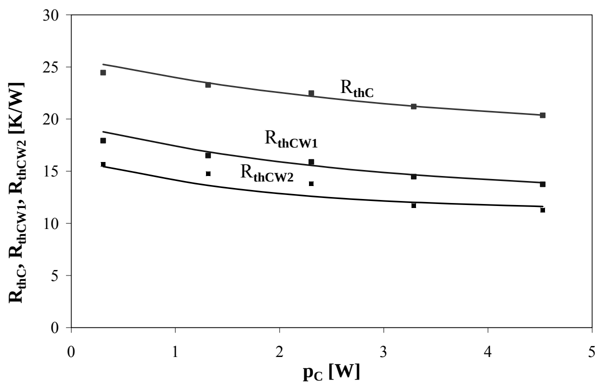
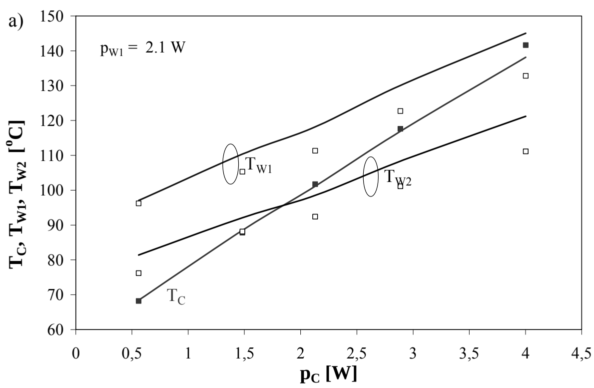


Fig. 7. Measured dependences of thermal resistance of the core R_{thC}, mutual thermal resistance between the core and the primary winding R_{thCW1}, mutual thermal resistance between the core and the primary winding R_{thCW2} on the power dissipated in the core p_C

As one can notice in both the considered figures the values of thermal resistance of the winding of R_{thW1} and the core R_{thC} are greater than the values of mutual thermal resistances R_{thWW} and R_{thW1C} and R_{thCW1} and R_{thCW2}, respectively. One observes also more efficient abstraction of heat generated in the core than in the winding, which is confirmed by the smaller values R_{thC} than R_{thW1}. It is the effect of greater area, where convection of heat for the core is bigger than for the winding. The values R_{thC} are even above 20% smaller than the value R_{thW1}.

Using the values of parameters collected in Table 2 and the thermal model of the transformer described with the equations (1-3) the values of temperature of components of the transformer at simultaneous dissipation of the power p_C in the core and in the primary winding p_{W1} are calculated.

Fig.8 presents the calculated and measured dependences of temperature of the core T_C and windings T_{W1} and T_{W2} on the power dissipated in the core at the steady state at the power dissipated in the primary winding p_{W1} equal to 2.1 W (Fig.8a) and 3.2 W (Fig.8b).



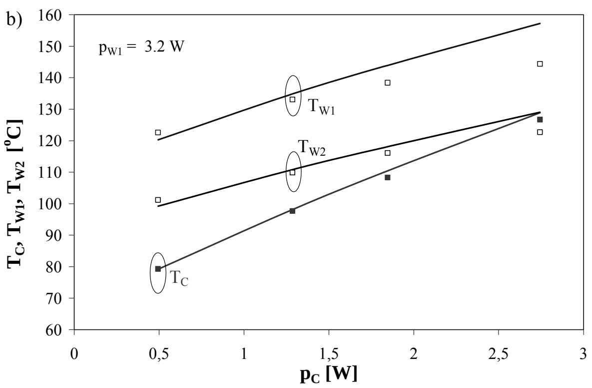


Fig. 8. Calculated and measured dependences of temperatures of the core and the windings on the power dissipated in the core p_C at the fixed value of the power dissipated in the primary winding p_{W1} equal to 2.1 W (a) and 3.2 W (b)

As one can observe, as a result of mutual thermal coupling between the core and the windings, an increase in the value of the power p_C causes a temperature rise not only of the core, but also the windings of the transformer. In either case one obtains monotonically growing dependences of each considered temperature from the power p_C. The observed differences between the performance of calculations and the measurements do not exceed 10^oC. This good agreement of the results of calculations and measurements proves correctness of the presented thermal model of the transformer.

Conclusions

In the paper the static thermal model of the planar transformer is proposed. In this model self-heating in the core and in the windings, as well as mutual thermal couplings between components of the transformer, are taken into account. The analytic equation describing the influence of the power dissipated in the primary winding and in the core on thermal resistances occurring in the model of the transformer is formulated.

The correctness of this model was verified experimentally and a good agreement between the results of calculations and measurements was obtained. The influence of orientation of the transformer on thermal resistances existing in its thermal model was also pointed out.

The proposed static thermal model of the transformer can be useful in designing electronic networks containing planar transformers. This model makes it possible to calculate values of temperature of structural components of such a transformer at the steady state.

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