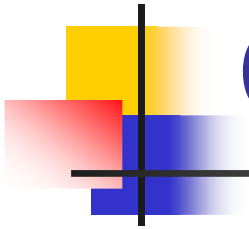
Compact Thermal Model of Planar Transformers

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Outline

- Introduction
- The form of the transformer compact thermal model
- The measurement methods
- Results of measurements
- Evaluation of the thermal model
- Conclusions

Introduction (1)

- Transformers are important components of electronic circuits.
- More and more frequently planar transformers are used, which are characterized with small dimensions and can be integrated with the PCB.
- During the operation of electronic components their temperature increases above the ambient temperature as the result of thermal phenomena.
- In order to calculate the value of the internal temperature of the electronic component at the well-known course of the power dissipated in this element the thermal model of this element is indispensable.
- Such a model can have the form of a detailed model described with the heat transfer equation together with suitable initial conditions and border conditions or it can be a compact model.

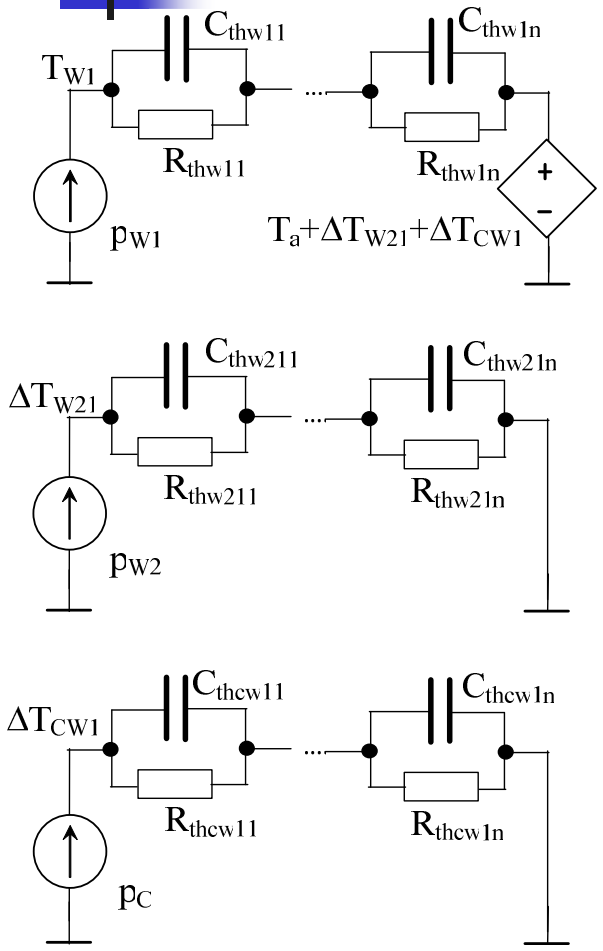
Introduction (2)

- The given in the literature compact thermal models of transformers have following disadvantages:
  - some of them omit differentiation of temperatures of the core and the windings,
  - in the other models only power losses in the windings of the transformer are taken into account, whereas losses in the core are omitted.
- In the previous Authors' paper the dc thermal model of the planar transformer is proposed.
- In this paper the dynamic thermal model of the planar transformer is proposed and the method of measurements parameters existing in this model are presented.

The form of the Transformer Compact Thermal Model

- Compact thermal models are often presented in the form of their network analogs, in which the current corresponds to the power dissipated in the modelled element, and the voltage - the temperature difference between structural components of the element.
- As it was shown in literature, in transformers there appears visible differentiation of the value of temperatures of the core and each winding at the nearly uniform distribution of temperature in each of the considered components of the transformer.
- The considered thermal model makes possible calculation of waveforms of temperature of the core and each of the windings.
- In this model both self-heating phenomena in the core and in the windings and mutual thermal couplings between these components of the transformer are taken into account.

The form of the Transformer Compact Thermal Model (2)



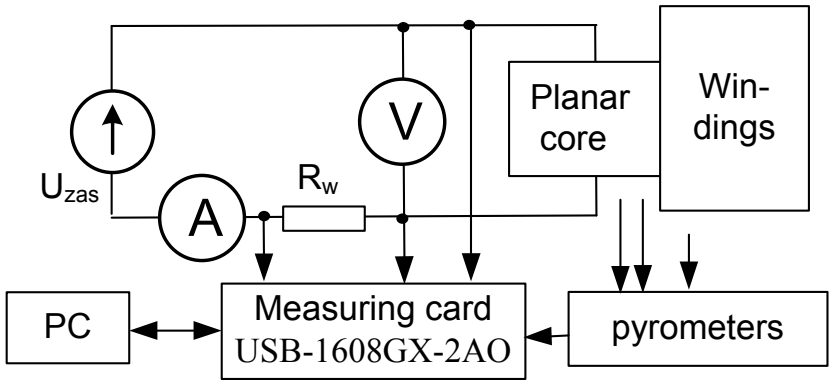
- In the thermal model of the whole transformer there appear together 3 blocks of identical structure to this one, shown in figure (for the primary winding).
- 3 subcircuit can be distinguished, which make possible:
  - calculation of the excess of temperature of the primary winding resulting from mutual thermal couplings between the core and the primary winding,
  - calculation of the excess of temperature of the primary winding resulting from mutual thermal couplings between the windings,
  - calculation of temperature of the primary winding T_{W1} resulting from self-heating phenomena in this winding and mutual thermal couplings between the primary winding and other components of the transformer.

The form of the Transformer Compact Thermal Model (3)

- Current sources p_{W1}, p_{W2} and p_C represent waveforms of powers dissipated in the primary winding, in the secondary winding and in the core, respectively.
- The controlled voltage source represents the influence of the ambient temperature T_a and mutual thermal couplings on temperature of the primary winding.
- RC Foster network models self transient thermal impedance of the primary winding and mutual transient thermal impedances between this winding and the secondary winding and the core.
- To describe this model waveforms of 3 self transient thermal impedances of each from the mentioned components of the transformer and 6 mutual transient thermal impedances between each pair of components of the transformer are indispensable.
- Because the heat flow between each from the pairs of components of the transformer is two-way identical, in the thermal model only 3, instead of 6, mutual transient thermal impedances are necessary.

The measurement methods

- A new method of measuring self transient thermal impedance of the core and mutual transient thermal impedances between the core and each of the windings is proposed.
- This method is based on the concept to measure the power dissipated in the power transformer and it is an extension of the method of measuring thermal resistance of the ferromagnetic core.
- This method is realized in the following set-up.



The measurement methods (2)

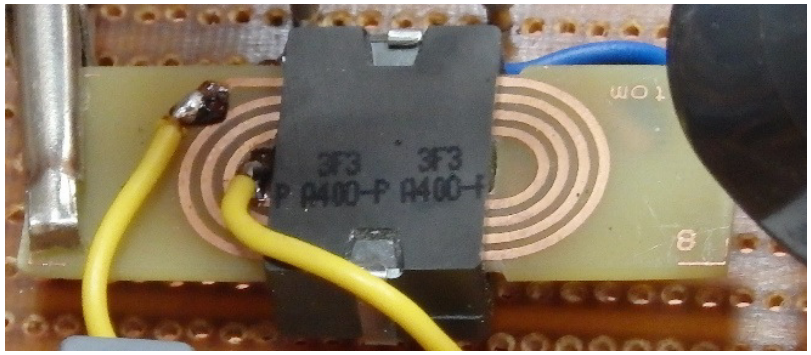
- In this method the core of the investigated transformer is stimulated by the direct current until the steady state is achieved.
- The current I_2 flowing through the core and the voltage drop on the core V_2 are measured.
- Next, in the moment t = 0, the power supply is switched off and waveforms of the core temperature $T_C(t)$, temperature of the primary winding $T_{W1}(t)$ and temperature of the secondary winding $T_{W2}(t)$ are measured with the use of pyrometers and are then registered.
- Finally, the considered self and mutual transient thermal impedances are calculated with the use of the following formulas

$$Z_{thC}(t) = \frac{T_C(t=0) - T_C(t)}{V_2 \cdot I_2} \qquad Z_{thCW1}(t) = \frac{T_{W1}(t=0) - T_{W1}(t)}{V_2 \cdot I_2} \qquad Z_{thCW2}(t) = \frac{T_{W2}(t=0) - T_{W2}(t)}{V_2 \cdot I_2}$$

- Using the Authors' algorithm and the measured waveforms of self and mutual transient thermal impedances the values of RC elements existing in the thermal model of the transformer are calculated.

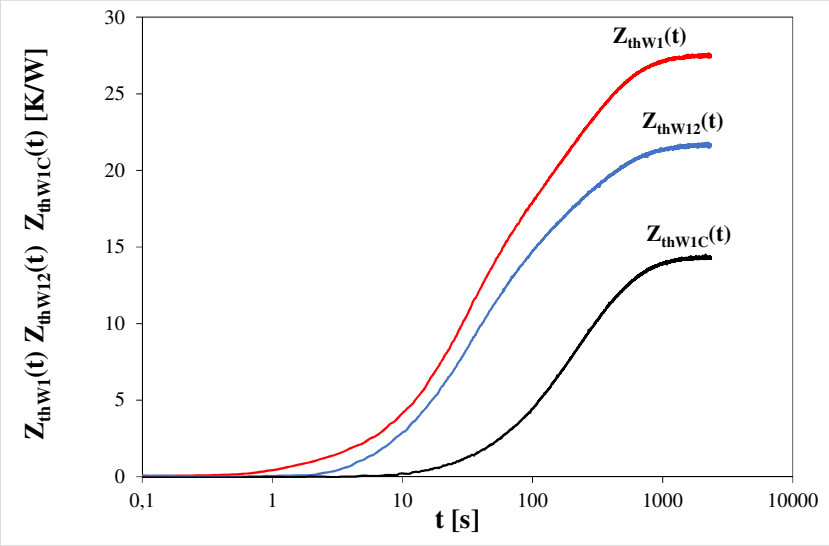
Results of Measurements

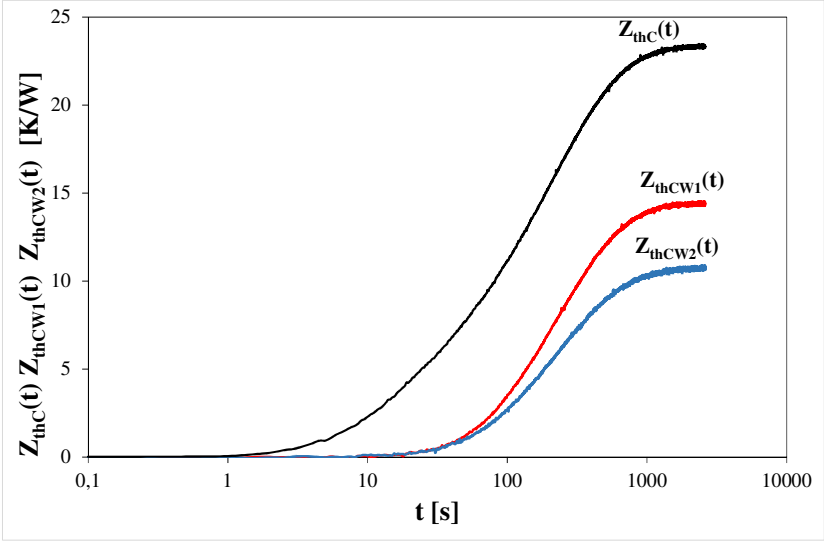
- Using the measuring-methods described above self and mutual transient thermal impedances occurring in the description of the thermal model of the transformer containing the planar ferrite core made of material 3F3 of the type E22/6/16R were performed.



- 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.

Results of Measurements (2)





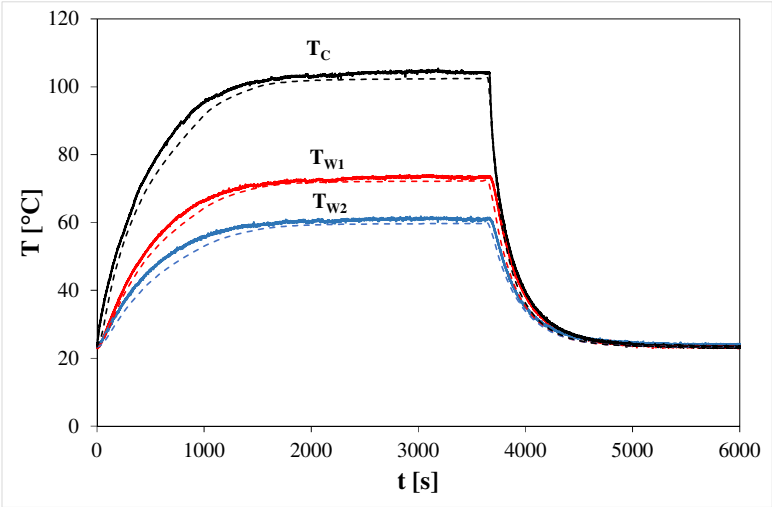
- The highest values are accepted by self transient thermal impedance of the primary winding and by self transient thermal impedance of the core
- Mutual transient thermal impedance between the primary winding and the core at the steady-state is even twice smaller than considered self transient thermal impedance .
- Waveforms of mutual transient thermal impedances are late with relation to the waveform $Z_{thW1}(t)$ even by over 100 s - $Z_{thW1C}(t)$

Evaluation of the Thermal Model

- In order to examine practical usefulness of the formulated thermal model of the transformer, waveforms of the temperature of the core and both the windings of the transformer were calculated using this model at stimulation with rectangular pulses of the power $p_C(t)$ dissipated in the core and in the primary winding $p_{W1}(t)$.
- In following figures calculated (dashed lines) and measured (solid lines) waveforms of temperature of the primary winding $T_{W1}(t)$, the temperature of the secondary winding of $T_{W2}(t)$ and temperature of the core $T_C(t)$ at dissipation in the core and in the primary winding, power of the shape of rectangular pulses of the value p_H are presented.

Evaluation of the Thermal Model (2)

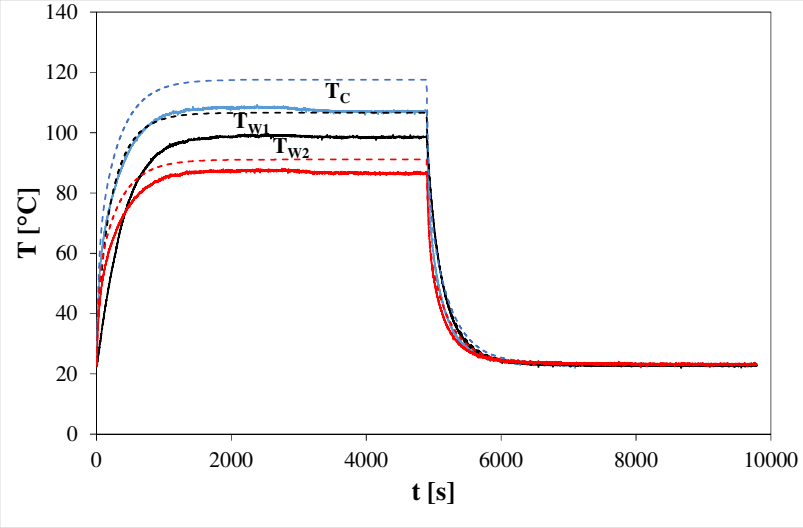
$p_{W1} = 0$ $p_{W2} = 0$ $p_{CH} = 3.4W$



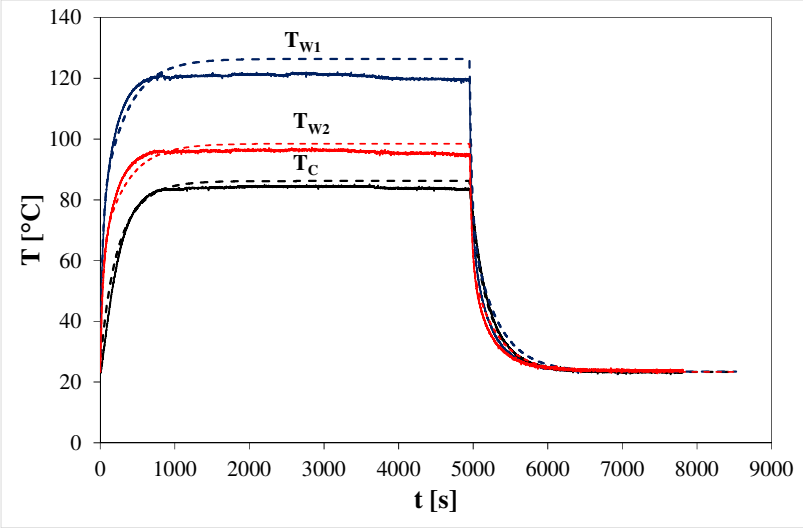
- The value of the core temperature is determined only by self-heating phenomena, and the windings temperature – by mutual thermal couplings.
- It is proper to notice that in the considered case the core temperature is even about 50^o C higher than temperature of the secondary winding.
- The indispensable time to obtain the steady state exceeds 2000 s.

Evaluation of the Thermal Model (3)

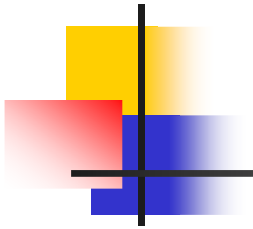
p_{W1H} = 2.3W p_{W2} = 0 p_{CH} = 2.1W



p_{W1} = 3.1W p_{W2} = 0 p_{CH} = 0.8W



- The good agreement between calculated and measured waveforms of temperature of the structural components of the transformer is obtained.
- This proves the correctness of the presented thermal model of this element and presented methods of the measurement of thermal parameters of the transformer.



Conclusions

- The compact thermal model of planar transformers is proposed.
- This model makes it possible to calculate waveforms of temperatures of the primary winding, of the secondary winding and of the core.
- The measurement methods of all self and mutual transient thermal impedances existing in the considered model are presented.
- The correctness of the presented model and measurement methods is verified for the planar transformer with the ferrite core.
- The presented results of measurements and calculations prove usefulness of the proposed model and measurement methods.
- The presented results of measurements and calculations prove that differences between the values of temperatures of the components of the considered planar transformers can be very big and exceed even 70^{o} C.
- Therefore, different temperatures of all the components of the transformer should be used in thermal models of the planar transformer.