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The compact thermal model of the pulse transformer

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ABSTRACT

This paper proposes the form of a compact thermal model of pulse transformer. This model takes into account self-heating and mutual thermal coupling between the windings and the core of the transformer. It allows the calculation of the waveforms of the core and windings temperature at a known waveform of the power dissipated in particular components of the transformer. The proposed model has a form of a RC network, representing the transformer's own and mutual transient thermal impedance. This network is excited by controlled current sources, representing the power dissipated in the windings and in the core of the transformer. The form of the elaborated thermal model, the method of determining the values of its parameters and the selected results of measurements and calculations performed with the use of the model are presented and discussed.

1. Introduction

The pulse transformer is one of the basic components of power electronic circuits, which are commonly used in electronic equipment [1,2]. Such a transformer consists of the ferromagnetic core and at least two windings [1,3]. Temperature influences essential properties of this element [4–6]. Therefore, it is important to know the value of the transformer temperature during its operation.

In every single winding and in the core of the transformer a self-heating phenomenon occurs, and in addition, mutual thermal interactions between these components are observed [4,7]. In order to calculate the temperature of each component of the transformer, the detailed models are typically used [3]. Such models make it possible to calculate time-spatial distribution of temperature in the transformer. However, because of high complexity of these models, their use in the analysis of electronic circuits is unjustified as it is very time consuming to carry out such calculations.

The concept of the compact thermal models has long been used for modelling thermal phenomena in semiconductor devices [8–14] and integrated circuits [15,16]. However, in the literature the compact thermal model of the transformer is presented in a small number of works, e.g. in [4,6]. In the model described in [6] only one internal temperature of the considered device is used to characterise its thermal condition. In turn, in the paper [4] different values of the temperature of the core and the windings are distinguished, but all the windings have the same value of temperature.

In this paper, which is an extended version of the paper [17], the compact thermal model of the pulse transformer taking into account self-heating in the ferromagnetic core and in every winding and mutual thermal interactions between the windings and between the core and the windings is proposed. This model exploits the idea of the devices own and mutual transient thermal impedances [7,9,13,18–20] used typically in modelling thermal properties of semiconductor devices.

In the following sections the description of the thermal model of the transformer and a manner of estimating values of the parameters of this model are presented. The paper presents also the results of a computer analysis performed with the elaborated model. The results of calculations are compared with the results of measurements.

2. The model form

In the proposed thermal model different values of each winding's and core's temperature can exist. For the simplest situation, when the transformer contains two windings only, the temperature T_i of each part of the transformer can be described using the following equation:

$$T_i(t) = T_a + \sum_{j=1}^{3} \int_0^t Z'_{\mathrm{th}ij}(\tau) \cdot p_j(t-\tau)d\tau \tag{1}$$

where T_a denotes the ambient temperature, i represents the name of the winding or of the core, $p_i(t)$ denotes the power dissipated in ith element of the transformer and $Z'_{\mathrm{th}ij}(t)$ represents the time

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derivative of the devices own (for $i=j$) or mutual (for $i \neq j$) transient thermal impedance in the transformer thermal model.

The transient thermal impedance can be modelled using the classical formula [10,14,19]

$$Z_{th}(t) = R_{th}\left[1 - \sum_{k=1}^{N} a_k \cdot \exp\left(-\frac{t}{\tau_{thk}}\right)\right] \tag{2}$$

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

The network representation of this thermal model is shown in Fig. 1. This representation has the form of the RC network excited by current sources representing values of the power dissipated in each winding and in the core.

In the presented model the electro-thermal analogy [10,12,14,21,22] is used. Voltages at nodes T_{W1}, T_{W2} and T_C denote temperature of the primary winding, the secondary winding and the core, respectively. RC networks of the Foster structure occurring between these nodes and voltage sources represent each winding's and the core's own transient thermal impedances. The voltage sources represent the sum of the ambient temperature T_a, and the temperature excess of various elements of the transformer caused by mutual thermal coupling with the other elements of the transformer. The temperature excesses of the windings and the core caused by the mutual thermal coupling are denoted by ΔT_{W12}, ΔT_{W21}, ΔT_{W1C}, ΔT_{W2C}, ΔT_{CW1}, ΔT_{CW2} and are calculated in the circuits containing RC elements representing mutual transient thermal impedances between the windings and between the core and the windings. These circuits are excited by current sources representing the power dissipated in the primary winding p_{W1}, the power dissipated in the secondary winding p_{W2} and the power dissipated in the core p_C.

The values of the elements R_{thi} and C_{thi} can be directly obtained using the values of the parameters existing in Eq. (2) and the following formulas:

$$R_{thi} = R_{th} a_i \tag{3}$$

$$C_{thi} = \frac{\tau_{thi}}{R_{thi}} \tag{4}$$

3. Estimation of the model parameters

The estimation of parameters values of the model described in Section 2 is realised in two stages. In the first stage each winding's and the core's own and mutual transient thermal impedances are measured with the use of electric or optical measuring methods. In the second stage, on the basis of the obtained waveforms of their own and mutual transient thermal impedances, the values of RC elements existing in the thermal model of the transformer are calculated with the use of the authors' algorithm.

According to the definition of the transient thermal impedance $Z_{th}(t)$ [10,18,19,23], in order to measure the time waveform of the internal temperature of the considered device, the excitation of power step is required. The measurement is performed using the indirect electrical method to measure the temperature of the windings and the infrared method—to measure the core temperature.

The measurements of the transformer's own transient thermal impedance of the primary winding and the mutual transient thermal impedance between the transformer windings and the mutual transient thermal impedance between the windings and the core are implemented in the measurement set-up shown in Fig. 2. In order to ensure the constant ambient temperature during the measurements, the test transformer is placed in a thermostat.

The primary winding of the investigated transformer is supplied with a DC voltage source E_P, the value I_P of the primary winding current is limited by the resistor R_W. In turn, the secondary winding is supplied with the DC voltage source E_S and the secondary winding current I_S is limited by the resistor R.

The winding temperature values are calculated on the basis of the measurements of the resistance of these windings. The primary winding resistance R_1 is equal to the quotient of the voltage V_P and the current I_P, whereas the secondary winding resistance R_2 is equal to the quotient of the voltage V_S and the current I_S. In turn, the core temperature is measured by the thermo-hunter, which detects the infrared radiation emitted by the measured device. The area of the measured surface of the core is a circle of the diameter equal to 2.5 mm. The value of the core temperature is measured at each 100 ms [25].

In order to calibrate the thermometric characteristics of the windings, the primary winding resistance R_{10} and the secondary winding resistance R_{20} are measured at small values of currents I_P

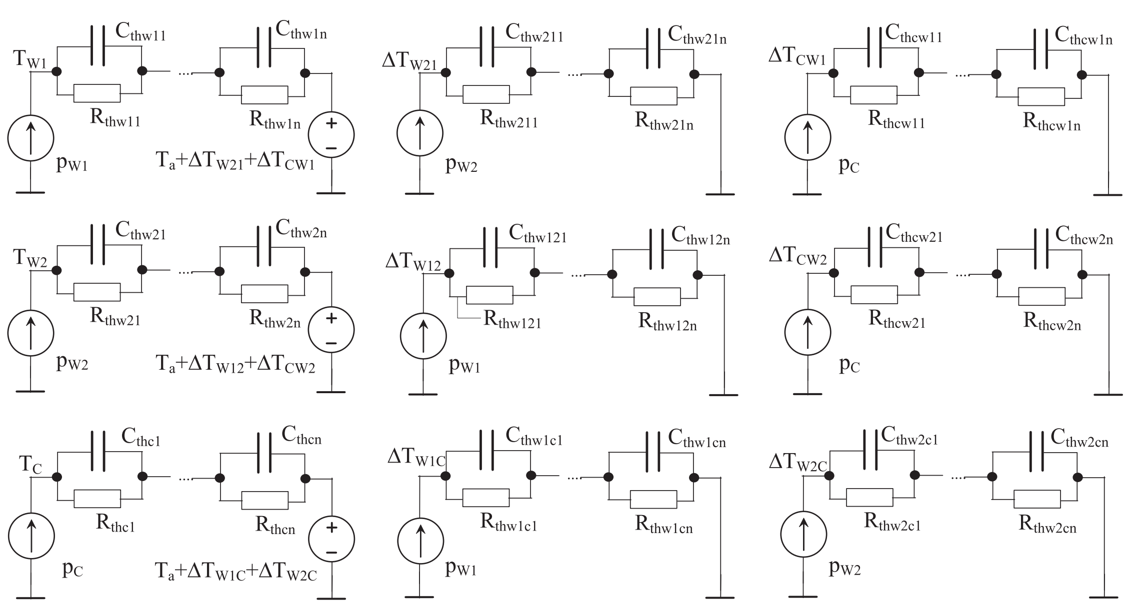

Fig. 1. The network representation of the compact thermal model of a pulse transformer.