Modelling nonisothermal electrical characteristics of ferrite cores

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Abstract. In the paper the problem of modelling an influence of thermal phenomena on electrical characteristics of ferrite cores is considered. A compact electrothermal model of the ferrite core is proposed. This model is dedicated to calculate dc and transient electrical characteristics of this core. The form of this model is presented, the method of parameters values estimation is described and some results of experimental verification of this model are shown for the planar core E22/6/16R made of material 3F3 by Ferroxcube.

1. Introduction

Ferrites are commonly used in electronics and power electronics circuits, in which they play a role of cores of inductors and transformers [1, 2, 3]. In these applications the most important role is played by magnetic properties of the considered materials characterised, among others by the magnetising curve B(H) [1, 4, 5]. However, during operation of magnetic elements (inductors and transformers) eddy currents are also induced in the core, which are one of the factors causing losses of energy in the core [1, 2, 6]. The value of eddy currents is inversely proportional to resistance of the core.

Ferrites belong to ceramic materials characterised with high resistivity [1]; yet, large geometrical dimensions of ferrite cores cause that this resistance does not exceed several kiloohms [7].

As it is commonly known, current-voltage characteristics of electrical elements depend on temperature [8, 9, 10, 11]. Due to self-heating phenomena the internal temperature of an electronic component is higher than the ambient temperature, and its value depends on power losses in this element [9, 10, 12, 13]. Characteristics of the electronic component calculated or measured with self-heating phenomena taken into account are called nonisothermal characteristics. In order to take into account these phenomena in computer analyses, electrothermal models of the considered elements are indispensable.

Such models are described in literature for many semiconductor devices [9, 10], inductors [3, 14] or transformers [15, 16]. For example, in the paper [8] the electrothermal model of ferromagnetic core is described, but this model takes into account the influence of thermal phenomena on magnetic properties of this core only. In the known literature there is no information about modelling an influence of thermal phenomena on electrical properties of ferrite cores.

In this paper the electrothermal model of the ferrite core making possible calculation of nonisothermal characteristics of this element is proposed, and the correctness of this model is verified experimentally for the selected ferrite planar core.

In Section 2 the form of the elaborated model is presented. In Section 3 the manner of the model
parameters estimation is described. Finally, the results of calculations and measurements of the core characteristics are compared in Section 4.

2. Model form
The presented model of the ferrite core belongs to groups of compact electrothermal models [8, 10, 12, 13, 14, 15, 17]. This kind of models make it possible to calculate terminal voltage and current of the modelled device and internal temperature of this device. It is assumed that in the modelled device the uniform temperature distribution is observed. Such models consist of the electrical model, describing the dependence between terminal voltages and currents of the considered element, and of the thermal model, describing the dependence of the internal temperature of the element on the power dissipated in it.

The worked out electrothermal model of a ferrite core is dedicated for SPICE software and it has a form of the subcircuit. The network representation of this model is shown in Fig. 1.

**Figure 1.** The network representation of the electrothermal model of a ferrite core

The presented model consists of two blocks: the electrical model and the thermal model. In the electrical model the voltage source $V_1$, the resistor $R_1$ and the controlled voltage source $E_R$ exist. This resistor represents the minimum value of resistance of the core. The voltage source $V_1$ of zero output voltage monitors the current of the core, whereas the voltage source $E_R$ describes the dependence of the core resistance on the current $i$ flowing through the modelled core and on the core temperature $T_R$.

The voltage on the voltage source $E_R$ is given by the following equation

$$ E_R = \left( m_1 \cdot \exp \left( -\frac{i}{n_1} \right) + m_2 \right) \cdot \exp \left( B_1 \left( 2 - \exp \left( -\frac{i}{n_2} \right) \cdot \frac{1}{T_R} - \frac{1}{T_0} \right) \right) + \left( m_3 \cdot \exp \left( -\frac{i}{n_3} \right) + m_4 \right) \cdot \exp \left( B_2 \left( \frac{1}{T_R} - \frac{1}{T_0} \right) \right), $$

where $R_0$, $B_1$, $B_2$, $m_1$, $m_2$, $m_3$, $m_4$, $n_1$, $n_2$, $n_3$, $n_4$ and $T_0$ are parameters of the model.

In turn, in the thermal model the voltage on the terminal $T_R$ denotes the internal core temperature. This temperature is calculated with the use of the nonlinear thermal network of the form proposed in [18]. This network consists of linear capacitors representing thermal capacitances and controlled voltage sources representing thermal resistances of this core. The dependence of thermal resistance on the dissipated power is taken into account. The voltage source $V_{Ta}$ models the ambient temperature.

The voltage source $E_P$ represents the power dissipated in the core and its value is equal to the product of current and voltage of the core. The voltage source $E_{Rth}$ describes the dependence of the core thermal resistance on the dissipated power $p_R$. This dependence has a form given by [18].
\[ R_{th} = R_{th0} + R_{th1} \cdot \exp \left( -\frac{P_R}{P_0} \right) \]  

(2)

where \( R_{th0}, R_{th1} \) and \( p_0 \) denote model parameters.

3. Manner of model parameters estimation

In order to use practically the elaborated model estimation of model parameters values is indispensable. These parameters are estimated using measurements and calculations.

Values of parameters describing electrical characteristics of the core are estimated by approximation of the measured dependences of the core resistance on current at the selected values of the ambient temperature \( T_a \).

In turn, parameters existing in the thermal model are estimated using the procedure described in [8]. The measured waveforms of transient thermal impedance of the core are measured using the method proposed in the paper [19]. On the basis of the estimated values of the core thermal resistance at different values of the power dissipated in the core the values of parameters existing in Eq. (2) are estimated.

As a result of the estimation procedure the following values of model parameters of the core E22/6/16R made of material 3F3 are obtained: \( R_0 = 3.6 \, \text{k} \Omega, m_1 = 0.53, m_2 = 0.38, m_3 = 0.61, m_4 = 0.17, m_5 = 0.65, m_6 = 0.7, n_1 = 3.2 \, \text{mA}, n_2 = 0.15 \, \text{A}, n_3 = 4.2 \, \text{mA}, n_4 = 0.125 \, \text{A}, B_1 = 1000 \, \text{K}, B_2 = 8500 \, \text{K}, T_0 = 300 \, \text{K}, R_{th0} = 15.1 \, \text{K/W}, R_{th1} = 11 \, \text{K/W}, p_0 = 5 \, \text{W}.

4. Results of calculations and measurements

The proposed model was verified experimentally for the planar ferrite core E22/6/16R made of material 3F3 by Ferroxcube [20]. This core is shown in Fig. 2.

**Figure 2.** The view of the investigated core with connectors

The results of calculations and measurements are presented in Figs. 3-8. In these figures the results of calculations are marked with lines, whereas the results of measurements - with points. During measurements the investigated core is situated in the thermal chamber with regulated temperature. In Figs. 3-6 the dc electrical characteristics of this core are presented, whereas in Figs. 7-8 – transient characteristics are shown. During measurements the core is treated as an resistor and classical measurement set-up for the measure dc characteristics of this element is used. The temperature of the core is measured using pyrometer.

Fig.3 illustrates the dependence of resistance of the investigated core on the current at the selected values of the ambient temperature.

As it is visible, resistance of the core is a decreasing function of current and temperature. It is worth to notice that a change in temperature by about 130°C causes even a six-time change in the core resistance, and a change in the current value from 1 to 10 mA causes even a triple fall in this resistance. The observed changes in the value of the core resistance are a result only of changes in the ambient temperature, because the power dissipated in the core is near zero and self-heating phenomena are omittable.

Fig. 4 illustrates the influence of the ambient temperature on the current-voltage characteristics of
the considered core (Fig.4a) and the influence of the current on the dependence of resistance of the core on the ambient temperature (Fig.4b).

![Figure 3](image)

**Figure 3.** The measured and calculated dependences of the core resistance on the current at the selected values of the ambient temperature

![Figure 4](image)

**Figure 4.** The measured and calculated current-voltage characteristics of the core (a) and the dependence of the core resistance on the ambient temperature (b)

As it is visible, both the ambient temperature and the current strongly influence on the resistance of the core. In the considered range of changes in these quantities the value of this resistance changes even six times.

In Fig. 5 the calculated and measured current-voltage characteristic of the considered core and the dependence of the core temperature on the voltage are shown.

![Figure 5](image)

**Figure 5.** The measured and calculated current-voltage characteristic of the investigated core (a) and the dependence of the core temperature on the voltage (b)

As it is visible, the obtained dependence i(v) is not a function in the mathematical sense. In this
characteristic the electrothermal breakdown is visible at the voltage exceeding 40 V. At this point the core temperature is equal to about 70°C. The temperature of the investigated core is an increasing function of the voltage and its value reaches even 200°C. The observed shape of the i(v) characteristics is a result of monotonically decreasing dependence of the core resistance on the current and a strong influence of temperature on this characteristic. The considered resistance decreases from about 7 kΩ at the current i = 1 mA to only 60 Ω at i = 0.35 A. An increase of the core temperature is slower and slower when the power dissipated in the core increases. This is a result of a decreasing dependence of the core thermal resistance on the dissipated power, described in the model using Eq.(2). This dependence is shown in Fig.6.

![Figure 6](image)

*Figure 6.* The measured (points) and calculated (line) dependence of the core thermal resistance on the dissipated power.

The shape of this dependence results from the fact that efficiency of heat convection is a decreasing function of the difference between temperatures of the heat source and the surroundings [21].

Fig. 7 illustrates waveforms of the core transient thermal impedance obtained at the selected values of the dissipated power in the core. Changes equal even to 30% of the value of considered waveforms at the steady state is observed. The cooling conditions during the measurements of dc and the transient characteristics changes. Therefore, in the transient analysis the values of parameters $R_{th0}$ and $R_{th1}$ are equal to 16.1 K/W and 12 K/W, respectively. The steady state is observed after 3000 s from switching-on the power. The process of core heating is visible for time $t > 100$ s.

![Figure 7](image)

*Figure 7.* The measured (solid lines) and calculated (dashed lines) waveforms of transient thermal impedance of the core at the selected values of dissipated power.

Fig.8 presents the measured waveforms of the core temperature (Fig. 8a) and the core resistance (Fig.8b). These waveforms were measured while the core was included in the circuit consisting of the voltage source $V_{SUP}$ connected in series with the resistor $R_S$ and the investigated core. This voltage
source generates the signal of the shape of the voltage step of the value equal to $V_{SUP}$. Investigations were performed for 3 values of $V_{SUP}$ equal to 40 V, 50 V and 60 V, respectively.

![Waveform images](image_url)

**Figure 8.** The measured (solid lines) and calculated (dashed lines) waveforms of the core temperature (a) and the core current (b) at different values of $V_{SUP}$

The observed waveforms of the core temperature are increasing functions, whereas the waveforms of the core resistance are decreasing functions. On the temperature waveforms the steady state is observed about 2000 s after the voltage jump. Maximum observed value of the core temperature exceeds even 200 °C. In turn, the core resistance decreases from over 4 kΩ to about 100 Ω only. The time indispensable to obtain the steady state of the dependence $i(t)$ is the longest for $V_{SUP} = 50$ V and the shortest for $V_{SUP} = 60$ V.

5. Conclusions

In the paper the form of the electrothermal model of the ferrite core is proposed, in which both electrical phenomena and self-heating effect are taken into account. It was shown that this model assured a good agreement between the results of calculations and measurements both at dc characteristics and transient waveforms.

In the presented characteristics of the ferrite core it is visible that the dependence of resistance of the considered core on the current has the shape similar to a NTC thermistor. Additionally, it is visible that in the dc characteristics of this core the electrothermal breakdown occurs. It is proper also to notice that as a result of the flow of the direct current through the considered core, its temperature increases even to 200°C, and an increase of this temperature causes a significant decrease in resistance of this core. This can have an essential influence on the value of eddy currents induced in the core when this element operates in inductors or transformers. When the core temperature increases, eddy current should be taken into account.

The presented model and the results of investigations could be useful for designers of magnetic devices with ferrite cores. It will be possible to correctly calculate power losses in the core using the proposed model of the ferrite core.

6. References

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