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Electrothermal Model of Ferromagnetic Cores

Streszczenie. *W pracy zaproponowano elektrotermiczny model rdzeni ferromagnetycznych dla programu SPICE, dedykowany do analizy układów energoelektronicznych. Przedstawiono postać modelu oraz sposób wyznaczania jego parametrów magnetycznych, geometrycznych oraz cieplnych. Poprawność prezentowanego modelu została zweryfikowana przez porównanie obliczonych i zmierzonych charakterystyk wybranych rdzeni wykonanych z różnych materiałów i pracujących przy różnych wartościach indukcji pola magnetycznego, częstotliwości i temperatury otoczenia oraz przy różnych warunkach chłodzenia. We wszystkich przypadkach uzyskano dobrą zgodność między wynikami obliczeń i pomiarów.* ***(Elektrotermiczny model rdzenia ferromagnetycznego)***

Abstract. *This paper presents an electrothermal model of ferromagnetic cores dedicated for SPICE software. The form of this model, dedicated to be used in power electronics applications, is presented and the procedure of estimating magnetic, geometric and thermal parameters of the presented model is proposed. The correctness of the proposed model is verified by comparing the calculated and measured characteristics of the selected ferromagnetic cores operating at different values of flux density, frequency, ambient temperature and cooling conditions. The satisfied agreement between the results of calculations and measurements is obtained.*

Słowa kluczowe: modele uśrednione, przetwornica boost, dławik, samonagrzewanie, SPICE
Keywords: Ferromagnetic cores, electrothermal model, parameter estimation

Introduction

Magnetic elements (choking-coils and transformers) containing ferromagnetic cores are important components of switch-mode power supplies [1, 2, 3]. These cores have non-linear characteristics and significantly influence magnetic properties of the mentioned elements [4, 5] and circuits containing these elements [2, 3, 6].

In the literature, many works are devoted to modelling properties of the ferromagnetic cores [3, 7, 8, 9]. Models of these cores described in the cited works can be divided into 3 groups. The first group includes models using straight-line segments (proposed by Preisach [7]) to describe the magnetization curve B(H). The second group of models uses a formal approach for modelling the magnetization curve and is called geometric models [8]. Most current models use a nonlinear analytical description proposed by Jiles and Atherton in the paper [9].

In the classical form, all these models ignore the influence of self-heating on the characteristics of the core. In contrast, in the papers [2, 3, 4, 5, 10, 11] some results of investigations are presented, which confirm the influence of temperature changes on the values of important parameters of the core, such as saturation flux density B_{sat}, magnetic permeability μ or the hysteresis loop area, which is proportional to the power loss in the core. In the extreme case, after exceeding the Curie temperature T_C, the core permeability decreases rapidly, reaching a value corresponding to the magnetic permeability of free air. In the papers [12, 13] the manner of modelling the hysteresis loop with the influence of temperature taken into account is presented. In these papers, the selected parameters of the Jiles-Atherton model, e.g. spontaneous magnetization, depend on temperature. The analysis of the influence of temperature on the hysteresis loop with the use of the Jiles-Atherton theory is shown in [14, 15].

On the other hand, the models of electronic components are indispensible in the process of designing and analysing electronic circuits. The accuracy of these models and a set of physical phenomena taken into account in them determine validity of the calculations results.

Currently, SPICE is the standard program for the analysis of electronic circuits and power electronic engineering [16, 17]. Many papers describe the problem of modelling magnetic elements [5, 7, 8, 9, 18, 19], but they do not include the influence of temperature on the characteristics of the core. Well-known in this area is the classical Jiles-Atherton model, which was also implemented in SPICE [20]. The manner of using PSPICE to modelling the hysteresis loop is described in [21]. In the same paper, the influence of the selected parameters of the Jiles-Atherton model on the shape of the hysteresis loop is also analysed.

As it results from [23, 24], the Jiles-Atherton model has many defects, which cause that the modelling magnetization curve does not reflect its character compared with the characteristics of real magnetic cores. Therefore, to describe new ferromagnetic models, the equations from the paper [9] are used.

Electrothermal models of the ferromagnetic cores are presented, e.g. in [22 - 25]. In the papers [3, 4] the electrothermal models of choking-coils are proposed. A part of these models is nonlinear electrothermal model of ferromagnetic cores. Unfortunately, these models do not take into account the hysteresis of the magnetization characteristic. The model described in the paper [22] incorporates self-heating caused by conversion of the heat energy lost in the core and a linear influence of temperature on the parameters of the Jiles-Atherton model. In the description of this model, there are a number of formal errors, which result in even a hundredfold decrease of the obtained values of saturation flux density and the coercive field [14]. The analysis of this model leads to the conclusion that in order to get the correct shape and extent of changes of the flux density *B* and the magnetic force *H*, it is necessary to remove the magnetic path length in several places in the PSPICE input file [23].

In turn, the electrothermal model of the ferromagnetic core presented in [23] uses a very simple description of power losses in the core. In this model losses are proportional to frequency and the square of the amplitude of flux density. Such a description is correct only for sinusoidal waveforms of flux density and the selected ferromagnetic materials.

In this paper the electrothermal model of the ferromagnetic core dedicated for SPICE, elaborated by the authors, is described. The presented model takes into account both magnetic and thermal phenomena occurring in the ferromagnetic core. This model belongs to the group of compact electrothermal models and it is designed for use in SPICE software. In this model only one core temperature T_R is used and the uniform spatial distribution of this temperature is assumed. At the formulation of this model, the classic Jiles-Atherton model form, supplemented with temperature dependence of the parameters of this model taken from [23] and a description of power losses in the core taken from [5, 14] are used. In contrast to previous papers, not only the influence of ambient temperature on characteristics of ferromagnetic core is considered, but also the changes of the core temperature resulting from self-heating phenomena and non-isothermal characteristics of these cores are presented.

In the next sections the form of the elaborated model is described, the manner of estimation of the model parameters values is proposed and some results of measurements and calculations of the characteristics of the selected ferromagnetic cores are shown.

Description of the model

The elaborated by the authors' model is implemented as a subcircuit in SPICE software. The network representation of this model is shown in Figure 1. In this model the input signal, representing the magnetic force H, is represented as the voltage between the terminal H and the ground. The flux density corresponds to the voltage on the terminal B. The voltage at the terminal P_{loss} corresponds to the power losses in the core. The voltage on the terminal T_R is equal to the core temperature.

The considered model consists of three blocks: the magnetic model, the power model and the thermal model. In the magnetic model the modified Jiles-Atherton model is implemented. The voltage source E_4 represents magnetization on the initial magnetization curve described by [14]:

(1) $$M_a = \left[\frac{B_{S0}\cdot\left(1+\alpha_{BS}\cdot\left(T_R-T_0\right)\right)}{\mu_0} - H_S\right]\cdot F\left(\frac{H+\alpha\cdot M_a}{A}\right)$$

where B_{S0} denotes saturation magnetic flux density on the reference temperature T_0 at the saturation magnetic force H_S, α_{BS} – the temperature coefficient of saturation magnetic flux density changes, T_R –core temperature, μ_0 – permeability of free air, α - the interdomain coupling parameter and A - the thermal energy parameter. All these parameters appear in the Jiles–Atherton model. F(x) is the Langevin's function, which is non-continuous at x = 0. Therefore, in the presented model the F(x) function replaces the Langevin's function in the classical Jiles–Atherton model and has the following form [14]:

(2) $$F(x) = \frac{x}{\sqrt{x^2+1}}\left[1-0.9\cdot\exp\left(-\frac{|x|}{2.5}\right)-0.1\cdot\exp\left(-\frac{|x|}{25}\right)\right]$$

The current of the voltage source V_{dMa} is equal to the time derivative dM_a/dt.

The voltage source E_5 represents magnetic flux density expressed by the formula

(3) $$B = \mu_0\cdot\left(H + M\cdot C_R\cdot y\right)$$

where T_C denotes the Curie temperature and y is described by the formula:

(4) $$y = \begin{cases} 1 & for\ T_R < T_C \\ 1-\left(T_R-T_C\right)\cdot 0.06 & for\ T_C < T_R < T_C+17 \\ 0 & for\ T_R > T_C+17 \end{cases}$$

The current of the voltage source V_{dB} is equal to the derivative dB/dt. The voltage on the controlled voltage source E_1 is equal to the magnetic force H and the current of the voltage source V_{dH} is equal to the derivative dH/dt. The voltage at M node denotes magnetization in the core. The current on the controlled current source G_1 is described by the formula [14]

(5) $$G_1 = -\frac{\left(M_a - M\cdot C_2\right)\cdot \mathrm{sgn}(dH/dt)}{C_1\cdot H_{C0}\cdot\left[1+\alpha_{HC}\cdot\left(T_R-T_0\right)\right]}\cdot\frac{dH}{dt} - \frac{C}{C_1\cdot(1+C)}\cdot\frac{dM_a}{dt} + M\cdot\frac{C_R}{R_C}$$

where sgn(z) denotes the sign of the z argument, C is the domain flexing parameter, H_{C0} – the coercive field at T_0 temperature and α_{HC} – the temperature coefficient of the coercive field changes. C_1 and C_R are capacitances of capacitors existing in the magnetic model, whereas R_C is equal to the resistance of the resistor connected in parallel to the controlled current source G_1.

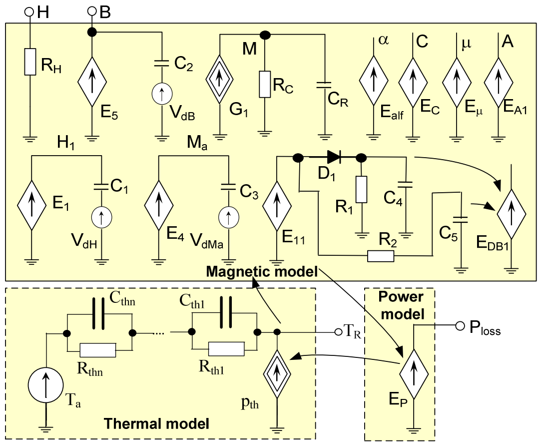

Fig.1. Circuit representation of a new electrothermal model of the ferromagnetic core

The controlled voltage sources E_{alf}, E_C, $E_{\square}$, E_{A1} are used to calculate the values of parameters α, C, μ and A existing in equations describing the magnetization characteristic B(H). The detailed description of these parameters taking into account the influence of temperature, is presented in [14].

The network consisting of the controlled voltage source E_{11}, the diode D_1, resistors R_1 and R_2, capacitors C_4 and C_5 is used to calculate the average value of flux density (the voltage on the capacitor C_5) and the maximum value of flux density (the voltage on the capacitor C_4). The voltage on the controlled voltage source E_{11} is proportional to the flux density B. The output voltage of the controlled voltage source E_{DB1} is equal to the magnitude of the flux density B_m.

In the power model only one controlled voltage source E_P exists. This voltage source represents power losses in the core P_{loss} and it is described by the formula from the paper [5] extended with the influence of temperature

(6) $$P_{loss} = V_e\cdot\left(B_m\right)^{\beta-\alpha}\cdot\left(1+\alpha_P\cdot\left(T_R-T_m\right)^2\right)\cdot\frac{P_{V0}}{T}\int_0^T\left|\frac{dB}{dt}\right|^{\alpha}dt$$

In Eq. (6), V_e is the volume of the core, P_{V0} denotes the volume density of power losses, α_P denotes the square coefficient of temperature changes of power losses, T_m – the temperature for minimum losses, T is a period of flux density of the magnetic field. In order to calculate the value of the integral existing in the equation (6) the standard SPICE function SDT is used.

The considered thermal model belongs to the group of compact thermal models, in which all the modelled elements have one internal temperature - in the case of the ferromagnetic core – the temperature T_R. In the presented model the electro- thermal analogy [26 - 30] is used. In this analogy, the current corresponds to the power dissipated in the element, while the voltage - to the temperature of each element of the heat flow path. The voltage at the node T_R denotes temperature of the core. This temperature can be expressed using the classical formula including a convolution integral [28, 30]

(7) $$T_R(t) = T_a + \int_0^t P_{loss}(x)\cdot Z_{th}^{'}(t-x)\cdot dx$$

where $Z'_{th}(t)$ denotes the thermal derivative of the transient thermal impedance.

The thermal model, corresponding to the equation (7), has the form of the RC network excited by the current source P_{th} representing values of the power dissipated in the core P_{loss}. The voltage source represents the ambient temperature T_a. The RC network of the Foster's structure represents transient thermal impedances $Z_{th}(t)$ of the core and characterizes altogether all mechanisms of the transfer of heat generated in the core, i.e. conduction, radiation and convection. This network can consist of many pairs of R_{thi} and C_{thi} elements, representing thermal resistances and thermal capacitances of the selected parts of the heat flow path.

Estimation of the model parameters

In order to use the presented model in a computer analysis, values of the parameters are indispensable. Many of these parameters can be obtained from the catalogue data of the magnetic material used for the construction of the considered core. Some methods of parameters estimation of the Jiles-Atherton model of ferromagnetic cores are proposed in [31 - 34]. In the paper [31] the genetic algorithm is applied and the dependence of the parameter k on the magnetic force is proposed. In the paper [32] it is shown that sets of the parameters values of the Jiles-Atherton model, which assure the best fit of the calculated and measured characteristics, depend to a considerable extent on the amplitude of the magnetic force. In the papers [33, 34] the method of least squares is used to delimit the parameters values of the Jiles-Atherton model. In turn, in the paper [35] the idea of local estimation of parameters values of the bipolar transistor model is proposed. The manner of estimating the parameters B_{R0}, B_{S0}, H_{C0}, H_S, H_X, M_X, μ_{i0}, α_R, α_C, α_S, α_U, T_C, V_e, with the use of the conception of local estimation, is described in [23].

Table 1. Values of the model parameters for the cores N27 and RTMSS

Parame-ter	B_{S0} [T]	α_{BS} [1/K]	H_S [A/m]	T_0 [K]	T_C [K]	H_{C0} [A/m]	α_{HC} [1/K]	P_{V0} [W/ $T^{\beta}/s^{-\alpha}/m^3$]
N27	0.485	-1.65×10^{-3}	1200	300	490	30	-3.33×10^{-3}	2.83
RTMSS	1	0	20×10^3	300	873	1.5×10^3	0	8.5
Parame-ter	C_1 [F]	C_2 [F]	B_{R0} [T]	α_{BR} [1/K]	μ_{ip}	α_μ [1/K]	M_X [A/m]	T_m [K]
N27	10^{-3}	1	0.25	-3.33×10^{-3}	2200	4.67×10^{-3}	2.54×10^5	353
RTMSS	10^{-3}	1	0.18	0	75	-1.91×10^{-3}	-7×10^3	298
Parame-ter	H_X [A/m]	M_{S0} [A/m]	R_3 [Ω]	C_R [F]	β	α	α_P [K^{-2}]	R_{th} [K/W]
N27	50	3.85×10^5	10^6	1	2.1	1.214	2.67×10^{-4}	15
RTMSS	7000	7.76×10^5	10^6	1	2.28	1.31	0	12

In turn, in the paper [36], the method of measuring transient thermal impedance of the core is formulated, whereas in the papers [23, 36], the method of estimating the values of thermal capacitances C_{thi} and thermal resistances R_{thi} on the basis of the measured waveform of transient thermal impedance is described. The value of R_{th} is estimated by averaging the waveform $Z_{th}(t)$ in the steady state, whereas the values of the parameters C_{thi} and R_{thi} are determined by the least square method.

The method of estimating the values of parameters describing power losses in the core is presented in [4].

In Table 1, the estimated values of parameters for two, arbitrary selected, ferromagnetic cores are collected. The first is the ferrite cube core made of N27 material by EPCOS, whereas the other is the ring powder core made from the alloy of iron with silicon and aluminium RTMSS 106075-2 by Arnold. Because in the further part of this paper the results of calculations corresponding to the steady state are presented and in order to shorten the time of calculations, the simplified form of the thermal model including one pair of elements R_{th} and C_{th} is applied. The estimated values of R_{th} of the examined cores are given in Table 1, while the used in calculations values of C_{th}, for both the considered cores, amount up to 1 mJ/K.

Results of calculations and measurements

In order to verify the correctness and usefulness of the elaborated model the magnetization characteristics B(H) of the selected ferromagnetic cores are calculated and compared with the measured characteristics. Additionally, the dependence of power losses on temperature, the amplitude of flux density and frequency are determined. As an example, Figure 2 shows the results of calculations (lines) and measurements (points) of the magnetization curve for the ferrite core made of material N27 by EPCOS, whereas Figure 3 presents the calculated (lines) and catalogue (points) magnetization curve for the powder core made of the material RTMSS.

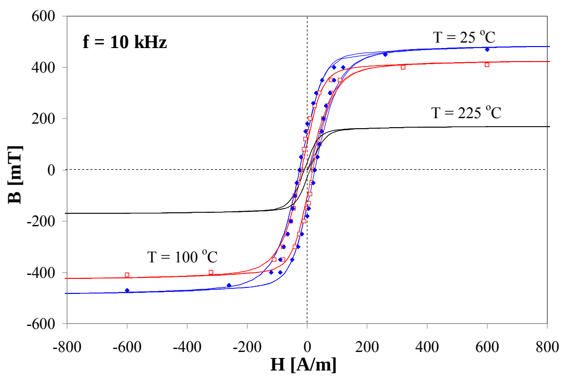

Fig.2. Calculated (lines) and measured (points) magnetization characteristics of the ferrite material N27

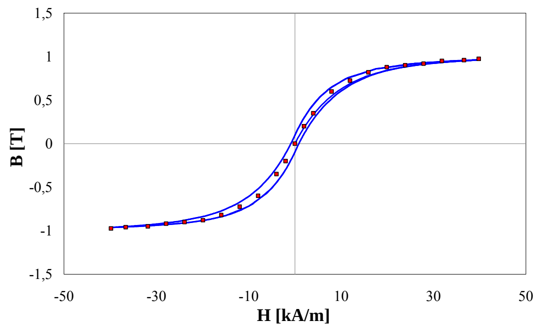

Fig.3.Calculated (lines) and measured (points) magnetization characteristics of the core RTMSS of the material 106075-2

As it is seen, the influence of temperature on the magnetization characteristics is different for the considered cores. For the ferrite core a visible decrease of saturation flux density and narrowing of the hysteresis loop at an increase of temperature are observed. In contrast, for the core RTMSS the magnetization characteristics practically do not depend on temperature.

Figures 4 and 5 present calculated (lines) and catalogue (points) dependences of the core losses on temperature, frequency and the amplitude of flux density for the considered cores.

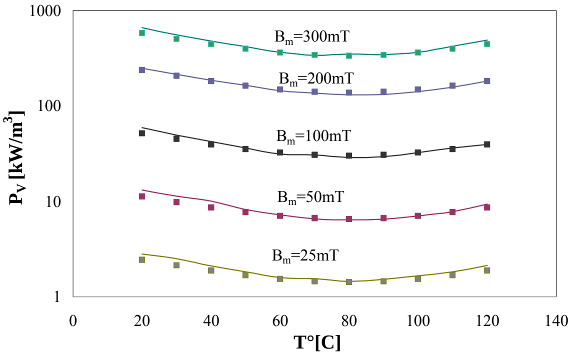

Fig.4. Calculated (lines) and catalogue (points) dependences of a core loss on temperature for the material N27

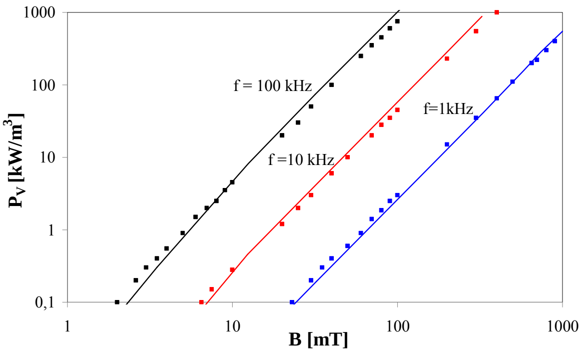

Fig.5. Calculated (lines) and catalogue (points) dependences of a core loss on the flux density for the material MS 106075-2

Figure 4 shows that in the ferrite core losses are an increasing function of the amplitude of magnetic flux density. It is worth noticing that for the specified value of the amplitude of magnetic flux density, the core losses achieve the minimum value at the temperature equal to about 80°C. In turn, in Fig.5 it is visible that an increase of the frequency and the amplitude of flux density cause an exponential increase in the core losses.

It is worth noticing that a good agreement between the calculations and measuring results is obtained, which confirms the correctness of the proposed model. The averaged value of the relative difference between the results of calculations and measurements does not exceed 10 %.

The results of measurements and calculations presented above correspond to the ideal cooling conditions of the investigated core. In turn, in Figs.6 and 7 the calculated characteristics of the ferrite core at the real cooling conditions are presented. In these calculations the volume of the core V_e is equal to $2x10^{-2}$ m^3. In these figures solid lines represents the characteristics obtained in the steady state, whereas the dashed lines – the characteristics obtained for the first period of the exciting signal.

As it is seen, selfheating results in a decrease of saturation flux density and a decrease of the core losses. The differences between the characteristics obtained at the ideal and real cooling conditions increase with an increase of frequency.

In the case presented in Figure 6, the temperature of the core in the steady-state exceeds the values of the ambient temperature by about 200 K. In turn, the dependence of the core temperature T_R in the steady-state on the amplitude of the flux density B_m is shown in Figure 8. As one can notice, the dependence $T_R(B_m)$ depends on the frequency f. As expected, at the small value of the amplitude B_m and frequency not a large increase of the core temperature is observed, and therefore there is a slight difference between the values of losses of the core obtained at the ideal and real cooling conditions. At the high values of the amplitude B_m, as a result of selfheating, losses in the core can increase even by 50%.

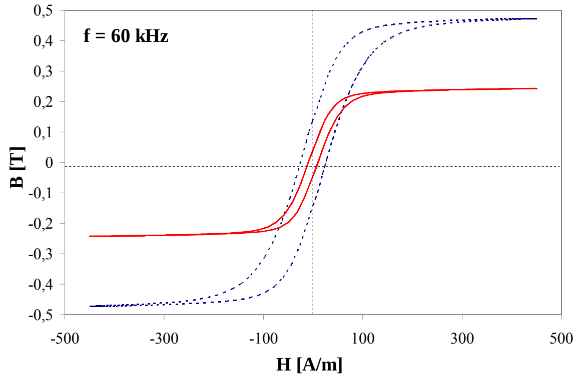

Fig. 6. Calculated magnetization characteristics of the ferrite core N27 at the ideal cooling conditions (dashed lines) and at the real cooling conditions (solid lines)

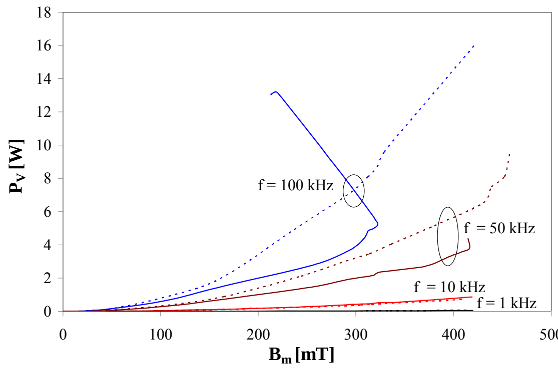

Fig. 7. Calculated dependence of the core losses on the amplitude of flux density for the ferrite core N27 at the ideal cooling conditions (dashed lines) and at the real cooling conditions (solid lines)

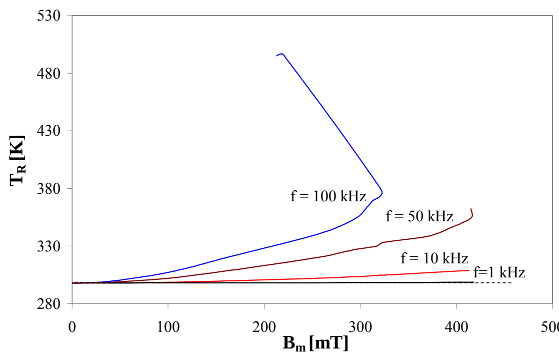

Fig. 8. Calculated dependence of the core temperature on the amplitude of flux density for the ferrite core N27 at the ideal cooling conditions (dashed lines) and at the real cooling conditions (solid lines)

For curves $P_V(B_m)$ and $T_R(B_m)$ obtained at the real cooling conditions at frequency f = 100 kHz, multi-value dependence is obtained at the big values of the magnetic force. The self-heating phenomenon causes a large increase in the core temperature, which causes the saturation flux density in the core visibly decreases.

Conclusions

In the paper the new form of electrothermal model of the ferromagnetic core and the method of parameters estimation values of this model are presented. This model takes into account magnetic and thermal phenomena in the core. The magnetic properties of the core are described using the equations formulated by Jiles and Atherton with some modifications proposed by the authors. In the new model a different analytical description of the initial magnetization curve is used and the influence of ambient temperature and the core temperature excess resulting from selfheating on the core magnetizing characteristic and power losses in the core are taken into account. A very important advantage of the proposed model is a possibility to calculate the internal temperature of the core, which can help the designer of an electronic circuit, including this core, to guarantee operation of this core in safe operating area.

The presented electrothermal model of the ferromagnetic core has the form of a sub-circuit for SPICE program. The proposed method of estimation of the parameters values of the model is based on the catalogue data of ferromagnetic material, as well as on the information on the dimensions of the core. The calculated characteristics using the formulated model show the satisfying agreement with the catalogue characteristics for the ferrite core and the powder core. The presented characteristics of the ferrite core prove that the influence of selfheating on these characteristics can be important, particularly in the range of high frequency.

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