Modelling power losses in an inductor contained in the boost converter

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***Abstract*—In the paper the literature models of power losses in magnetics materials and elements are analysed. Power losses were calculated for an inductor core made of ferrite material F867 used in the boost converter and taking into account the triangular shape of the waveform of magnetic flux density in this core. The results of investigations show that in order to correctly calculate power losses in magnetic materials and elements, it is necessary to take into account simultaneously the influence of frequency and temperature on parameters of the used ferromagnetic material.**

Keywords— power losses, Steinmetz equation, ferromagnetic materials, inductors, boost converter, modelling

I. INTRODUCTION

Watt-hour efficiency is one of the most important parameters of power electronics circuits. The growing demand for low power and high watt-hour efficiency forces designers of electronic devices to thoroughly analyse power losses dissipated in the components of the designed equipment, such as dc - dc converters.

Dc - dc converters, which are used to convert electrical energy in power supply, besides semiconductor devices, also contain magnetic elements, which are used to store electrical energy [1]. In the literature, a lot of papers are devoted to modelling power losses in semiconductor devices, e.g. [2, 3, 4, 5, 6, 7, 8, 9]. However, in recent years, more and more papers are focused on modelling power losses in magnetic elements [1, 10, 11, 12].

Power losses in magnetic elements can be divided into power losses occurring in the applied ferromagnetic material, which is used to build the core of magnetic elements and losses in the winding [3].

Power losses in magnetic materials belong to two groups containing eddy current losses, hysteresis losses and residual losses [3]. Values of power losses components depend on the type of magnetic material, peak values of magnetic flux density and changes of the shape of the magnetic flux density waveform and its frequency [3, 10]. Hysteresis losses are typical for powder materials used in circuits, in which frequency is in ranges from 10 kHz to 1 MHz [3]. In turn, power losses generated by eddy current are the dominant component of power losses in cores made of metal materials (amorphous materials, steel sheets) used in low-frequency circuits - up to 10 kHz [3, 11].

In the available literature models of such magnetic elements as an inductor or a transformer it is often assumed that the main source of power losses in magnetic elements are losses resulting from properties of the applied magnetic materials and nonlinear characteristics of magnetisation [1, 10, 13]. The first formulated model of power losses in ferromagnetic cores is the Steinmetz model [14], which became the starting model for many authors [13, 15]. However, this model does not allow for precise determination of power losses in the magnetic core of the inductor operating in the dc-dc converters, due to limitation relating to the sinusoidal shape of magnetic flux density. The dependence of power losses in the magnetic material proposed in the paper [14] has the form

$$P_{loss} = k \cdot f^{\alpha} \cdot B_m^{\beta} \tag{1}$$

where k, α, β are material parameters, B_m – the amplitude of magnetic flux density, f – frequency.

The aim of this paper is to verify usefulness of the selected models of power losses in magnetic materials available in the literature. In Section 2 the literature models and authors' models of power loses occurring in magnetic materials are discussed, Section 3 presents the method of the analysis and Section 4 presents the results of calculations obtained using the selected models.

II. THE SELECTED METHOD OF ESTIMATION OF POWER LOSSES IN FERROMAGNETIC CORES

As it was mentioned in Section 1, more and more papers concern modelling power losses in magnetic materials.

For example, in the paper [1] a dynamic model of an inductor dedicated to buck converters was proposed. This model consists of 3 blocks. Power losses in the core are calculated on the basis of the area of the magnetising curve B(H). The 5th degree polynomial was used to describe the dependence of B(H). Unfortunately, in the cited paper no analytical dependence describing losses in the ferromagnetic core was formulated. The presented results of investigations concern an inductor containing the core made of iron alloy with silicon and aluminium.

In the paper [13], a model i^2GSE of power losses in magnetic materials was proposed. This is an extended version of the modified Steinmetz model (iGSE). The model discussed in the cited paper requires the use of 5 to 8 parameters and additionally takes into account the relaxation effect. In order to determine power losses in magnetic materials, a different shape of magnetic flux density, i.e. triangular or trapezoidal, was considered. The results of investigations presented in the cited paper were carried out for the toroidal core R42 made of ferrite material N87 by EPCOS. Due to the complicated description and the lack of information about estimation of parameters occurring in the description of power losses, this model is difficult to implement.

In turn, in the paper [15] a model of power losses in magnetic materials including hysteresis losses, eddy current losses and residual losses was proposed. The proposed model is a modification of the Steinmetz model. In this model 2D and 3D transient analysis using the finite element method is used for sinusoidal and triangular waveforms of magnetic fluxes. Difficult dependences used in the considered model do not allow for simple calculations of power losses in magnetic materials.

In the paper [16] a modification of the Steinmetz model named GSE was proposed. In contrast to the classic Steinmetz model, this model is dedicated to different shapes of magnetic flux density. In order to obtain any shape of magnetic flux density, effective amplitude and effective frequency were used. The results of calculations presented in this paper relate to a transformer containing the MnZn 3C85 ferrite core.

In turn, in the paper [17] a method for modelling power losses in ferrite cores, taking into account the influence of frequency was proposed. These losses were divided into low-frequency which correspond to hysteresis losses and high-frequency losses corresponding to eddy current losses and residual losses. The cited paper concerns mainly the description of eddy current losses and residual losses. However, the analytical form of the discussed description of power losses is not given. The investigations were carried out for the Philips 3EP ferrite core.

In the paper [18] the procedure for formulating the general model of power losses in laminated sheets based on the small amount of data was proposed for frequency up to 2 kHz. This model takes into account hysteresis losses, eddy current losses and residual losses dependent on frequency and amplitude of magnetic flux density, which were taken into account by coefficients modifying the Bertotties model of the form

$$p_{Fe} = B_m{}^2 \cdot f \cdot \left[k_h(f, B_m) + f \cdot k_e(f, B_m)\right] \qquad (2)$$

where k_h and k_e are material coefficients depending on frequency f and amplitude of magnetic flux density B_m. The dependences, $k_h(B_m)$ and $k_e(f)$, $k_e(B_m)$ were presented in the paper [14], but the authors of the cited paper did not present any description of the dependences $k_h(f,B_m)$ and $k_e(f,B_m)$.

Among all the models discussed in this section, only models from papers [10, 11, 14, 19] are verified due to the simple form and the information on parameters values of the investigated magnetic materials. For example, in [10] a method of modelling power losses in magnetic materials for sinusoidal and triangular waveforms of magnetic flux density is presented. The proposed solution is an extension of the classic Steinmetz model and was named Natural Steinmetz Extension (NSE). In the paper [10], it was noticed that the coefficients α, β and k_w of the proposed model significantly depend on frequency and temperature. Yet, it was not explained how and no dependence describing the influence of temperature and frequency on these parameters was given.

The dependence describing the power losses for the sine wave of magnetic flux density, proposed in [10] has the form:

$$P_{NSE} = \left(\frac{\Delta B}{2}\right)^{\beta-\alpha} \cdot \frac{k_N}{T} \int_0^T \left|\frac{dB}{dt}\right|^{\alpha} dt \qquad (3)$$

where k_N is material parameter, T – period of magnetic flux density with the peak-to-peak value ΔB.

In turn, for the triangular waveform of magnetic flux density, the proposed dependence describing power losses has the form:

$$P_{NSE} = k_N (2f)^{\alpha} \cdot B_m{}^{\beta} \cdot \left(D^{1-\alpha} + (1-D)^{1-\alpha}\right) \qquad (4)$$

where D is the rise time of B(t) waveform.

In the paper [11] the dependence describing power losses in magnetic materials, which takes into account the influence of temperature and frequency of losses and parameter β was proposed, The investigations were carried out for ferrite F867 and powder (-26) material and compared with the catalogue data – the good agreement was obtained.

The proposed dependence for the sinusoidal waveform of magnetic flux density takes the form:

$$\begin{aligned} P_v = P_{v0} \cdot f^{\alpha} B_m^{\beta} \cdot (2 \cdot \pi)^{\alpha} \cdot \left(1 + \alpha_p \cdot (T_R - T_m)^2\right) \cdot \\ (0{,}6336 - 0{,}1892 \cdot \ln(\alpha)) \end{aligned} \qquad (5)$$

where α_p is the temperature coefficient of losses in the ferromagnetic material, T_R is the core temperature, T_m - temperature, at which the material has the smallest losses, and P_{v0} parameter has the form

$$P_{v0} = a \cdot \exp\left(-\frac{f + f_0}{a_3}\right) + a_1 \cdot (T_R - T_m) + a_2 \cdot \exp\left(\frac{f - f_2}{f_1}\right) \qquad (6)$$

where a, a_1, a_2, a_3, f_0, f_1, f_2 are material parameters. In turn, β parameter has the form

$$\beta = \begin{cases} 2 \cdot (1 - \exp(-T_R/\alpha_T)) + 1.5 \; if \; 1 - \exp(-T_R/\alpha_T) > 0 \\ 1.5 \;\; if \; 1 - \exp(-T_R/\alpha_T) < 0 \end{cases} \qquad (7)$$

where α_T is material parameter.

For the triangular waveform of magnetic flux density, power losses in magnetic material can be calculated from the dependence [12]:

$$P_V = P_{v0} \cdot f^{\alpha} B_m^{\beta} \cdot 2^{\alpha} \cdot \left(1 + \alpha_p \cdot (T_R - T_m)^2\right) \cdot \left(D^{1-\alpha} + (1-D)^{1-\alpha}\right) \; (8)$$

In turn, in [19] an electrothermal model of the inductor and the method of estimation its parameters were presented. This model takes into account both winding losses as well as losses which depend on properties of ferromagnetic material used to make the core of the considered element. It is worth noticing that the model described in [19] is dedicated to dc-dc converters, in which the current of the inductor has a triangular waveform. The dependence describing power losses occurring in this element has the form:

$$P_R = V_e \cdot \left(\frac{\Delta B}{2}\right)^{\beta-\alpha} \cdot \left(1 + \alpha_p \cdot (T_R - T_m)\right)^2 \cdot \frac{P_{v0}}{T} \cdot \int_0^T \left|\frac{dB}{dt}\right| dt \; (9)$$

where V_e – is a equivalent volume of the core.

III. THE METHOD OF ANALYSIS

Models presented in Section 2 were used to calculate power losses in the core of the inductor contained in the boost converter (Fig.1).

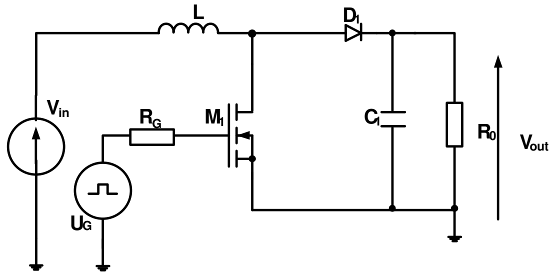

Fig.1. The diagram of the boost converter

In the examined circuit, the diode and the transistor were modelled as ideal electronic switches and the only source of power losses is the inductor.

In order to calculate power losses in magnetic materials whose dependencies are given in Section 2, it is necessary to know the amplitude of magnetic flux density, which can be calculated using the formula [20]

$$B_m = \frac{L \cdot \Delta I_L}{z \cdot S_{Fe}} \tag{10}$$

where S_{Fe} is cross-section area of the core, z - the number of turns, and the peak-to-peak value of the inductor current ΔI_L is calculated using the formula [21]

$$\Delta I_L = \frac{V_{in} \cdot d \cdot T}{L} \tag{11}$$

where V_{in} is the value of the input voltage of the boost converter.

As can be seen from the form of the formula (8), the value of the amplitude of magnetic flux density depends only on the number of turns, inductance, cross-section area of the core, the input voltage of the converter, the duty cycle and the period of the considered signal. It is worth noticing that the converter operation mode does not influence power losses of the inductor core.

IV. RESULTS OF CALCULATIONS

In order to verify the correctness of models proposed in [10, 11, 19, 21] used to calculate power losses in materials and magnetic elements, two sets of calculations were performed. The first set concerns calculations of power losses density in a ferromagnetic material for sinusoidal magnetic flux density.

In turn, the second set concerns calculations of power losses in the ferromagnetic core used to build the inductor in the boost converter, taking into account the triangular waveform of magnetic flux density. The investigations were carried out for the toroidal core made of ferrite material F867 with the outside diameter of 102 mm, the internal diameter equal to 57.3 mm and the height equal to 33 mm.

Figure 2 presents the calculated and measured dependences of power losses on the amplitude of magnetic flux density in a wide range of frequency for two values of temperature. The points denote the catalogue data, the dotted lines - the results obtained using the classical Steinmetz equation (1), and the solid lines - the results of calculations obtained using the model proposed in the paper [11].

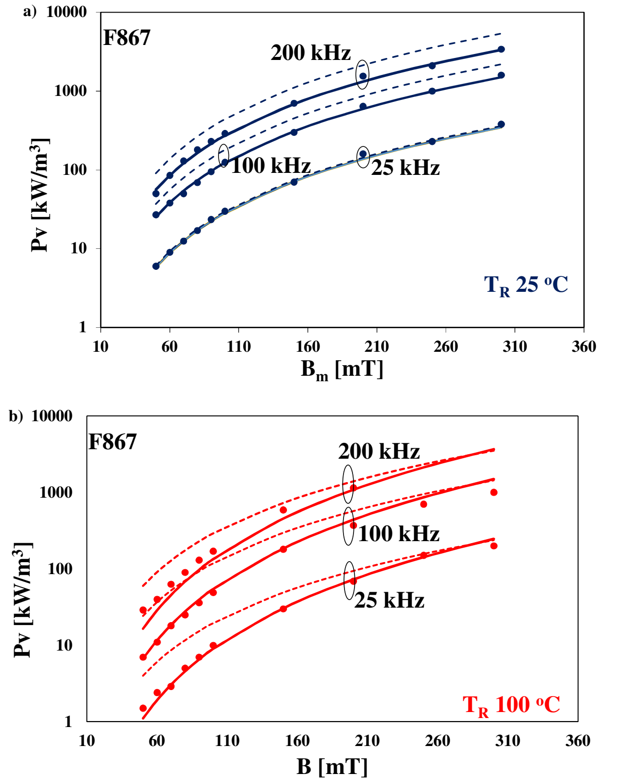

Fig. 2. The measured and calculated dependence of power losses per unit volume of F867 ferromagnetic material on the amplitude of magnetic flux density for temperature equal to: a) 25 °C, b) 100 °C

As it is visible, the good agreement was obtained between the results of calculations using the model proposed in the paper [11] and the catalogue data. Therefore, in the investigations, the model from [11] will be treated as a demonstration model. Noteworthy is also the fact that the classical Steinmetz model does not take into account the influence of temperature on the $P_v(B_m)$ dependence. Figure 3 shows the dependence of density of power losses and the calculated error of power losses in ferrite material on the amplitude of magnetic flux density at two values of frequency equal to 50 and 200 kHz, respectively.

In order to illustrate the influence of the applied models of power losses on properties of the boost converter, the calculation error of power losses in the inductor core as a function of frequency was calculated for two values of the core temperature T_R equal to 25 and 100 °C, respectively, and for two values of the input voltage equal to 12 and 100 V, respectively (Figs. 8-9). This error was calculated using the following dependence

$$\delta_{PV} = \left| \frac{P_L - P_M}{P_M} \right| \tag{12}$$

where P_L is the value of power losses calculated using one of the considered literature models, and P_M - the value of power losses calculated using the model proposed in the paper [11].

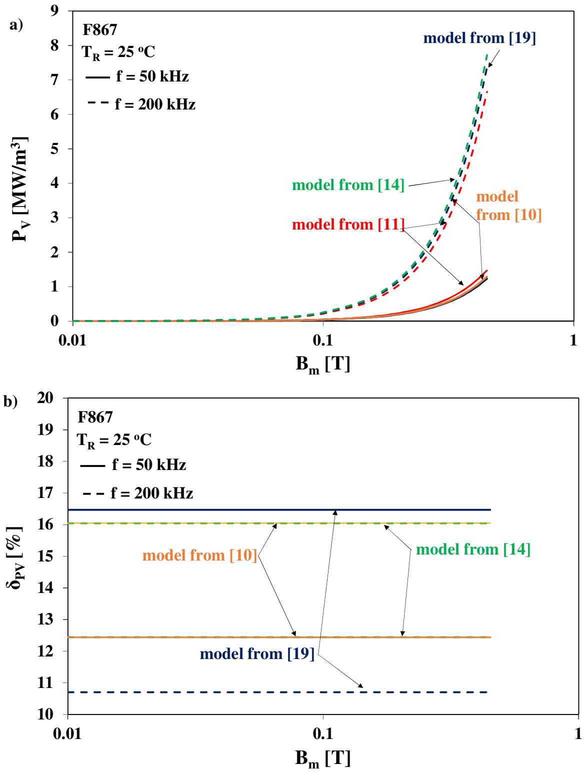

Fig.3. The calculated dependence of: a) power losses in ferrite material F867 and b) calculation error on the amplitude of magnetic flux density at frequency equal to 50 and 200 kHz, respectively.

As it is visible, an increase in frequency and magnetic flux density amplitude causes even a five-time-increase of magnetic material losses. In addition, it is worth noting that omitting influence of frequency and temperature on properties of magnetic materials causes an increase of power losses in the considered material up to 15%.

Figure 4 presents the dependence of power losses density in the considered material on frequency at two values of temperature equal to 25 and 100 °C, respectively.

From the dependences presented in Figure 4, it can be seen that the rice of temperature causes more than a double-power-losses-increase in magnetic material. The models proposed in [10, 14] do not take into account the influence of temperature on power losses in magnetic material, causing more than twofold overestimation of these losses at temperature equal to 100 °C.

Figures 5 - 7 show the results of calculations of power losses in the considered inductor core contained in the boost converter and the calculation error of power losses at two values of frequency of the control signal equal to 50 and 200 kHz, respectively.

As it can be seen from the dependences presented in Fig. 5a power losses in the ferromagnetic core of the inductor increase significantly with an increase of the input voltage V_{in}, obtaining the value even 150 W at V_{in} = 12 V and f = 50 kHz. It is worth noticing that an increase of frequency from 50 to 200 kHz causes a decrease in power losses in the inductor core even by 75%. In addition, it can be noticed that while omitting the influence of temperature and frequency on the parameters of magnetic material a reduction of the value of power losses to 30% at frequency f = 200 kHz is observed.

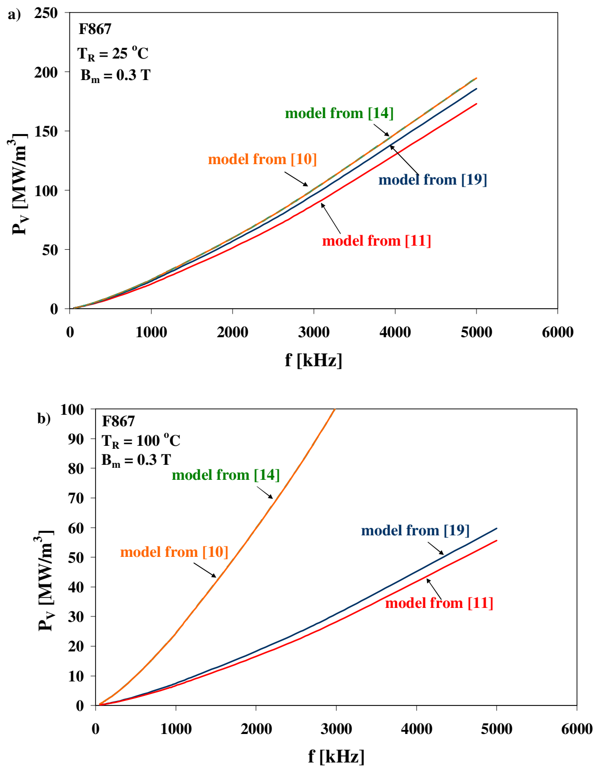

Fig.4. The dependence of power losses density in ferrite material F867 on frequency for two values of temperature equal to a) 25 and b) 100 °C, respectively.

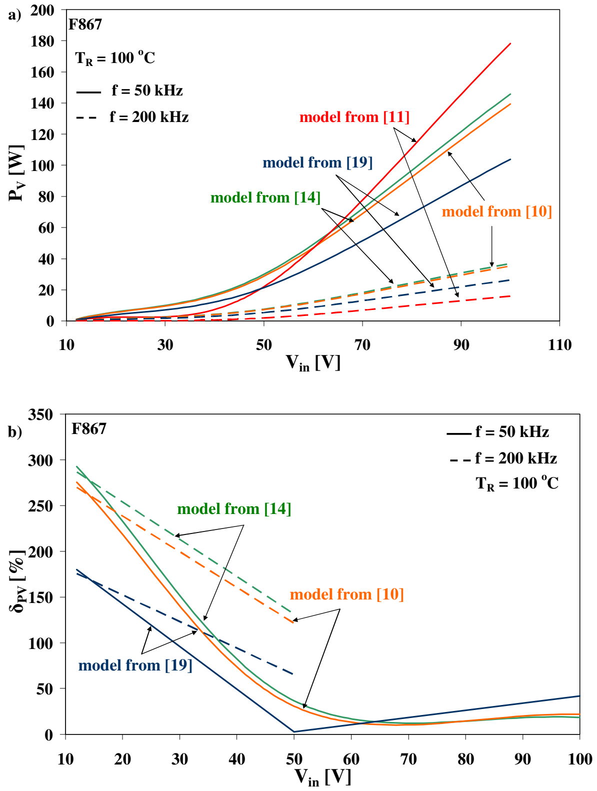

Fig. 5. The dependence of: a) power losses in the ferrite core and b) the calculation error of power losses on the input voltage at two values of control signal frequency equal to 50 and 200 kHz, respectively.

Figs. 6 - 7 show the dependence of power losses in the ferrite core F867 and the calculated value of the power losses error on frequency for two values of the core temperature equal to 25 and 100 °C respectively at V_{in} = 12 V (Fig.6) and V_{in} = 100 V (Fig.7), respectively.

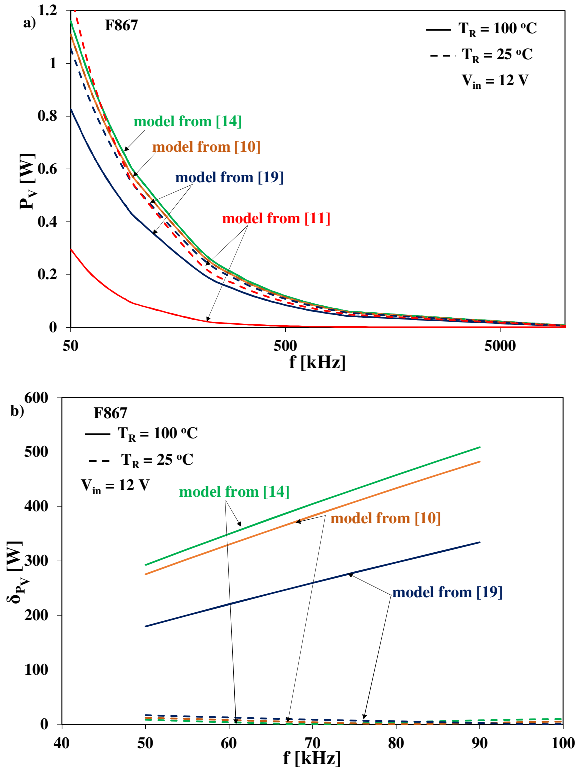

Fig. 6. The dependence of a) power losses in the ferrite core F867 and b) the error of power losses calculations on frequency at two values of the core temperature.

In turn, from the dependences shown in Figures 6 and 7, it can be seen that a rise of temperature causes a significant reduction of power losses in the inductor core for both the considered values of the input voltage. It is noteworthy that at the lower value of the input voltage the largest difference between the calculated power losses for both the considered values of the core temperature is observed in the frequency range from 50 to 200 kHz. For the higher value of the input voltage the largest difference between power losses in the core at both the considered values of the core temperature occurs in the frequency range from 200 to 600 kHz. In addition, it should be noted that omission of the influence of temperature, the triangular shape of magnetic flux density and frequency on parameters of magnetic materials in models [3, 6] causes even a double increase of power losses in the inductor core at the value of the input voltage equal to 100 V and even six times with the input voltage of 12 V.

As it can be seen, the largest calculation error was obtained using the classical Steinmetz model for both the considered core temperatures. In addition, it is observed that omitting the influence of temperature on properties of magnetic material in the model causes calculation errors more than 5 times bigger than the models taking into account temperature. Noteworthy is also the fact that the high error value was also obtained for the model described in [19], due to omission of the influence of temperature on the material parameter β and the influence of frequency and temperature on the parameter P_{v0}.

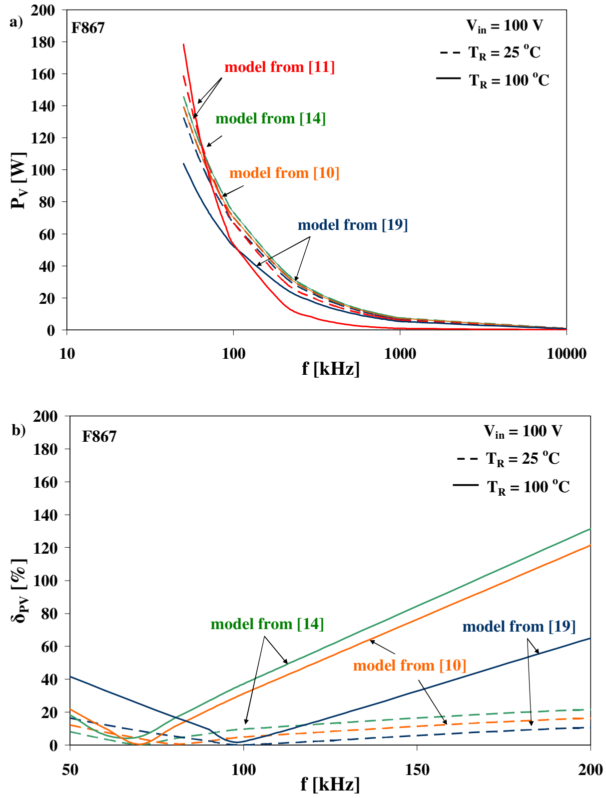

Fig. 7. The dependence of a) power losses in the ferrite core F867 and b) the power losses error on frequency for two values of the core temperature and V_{in} = 100 V

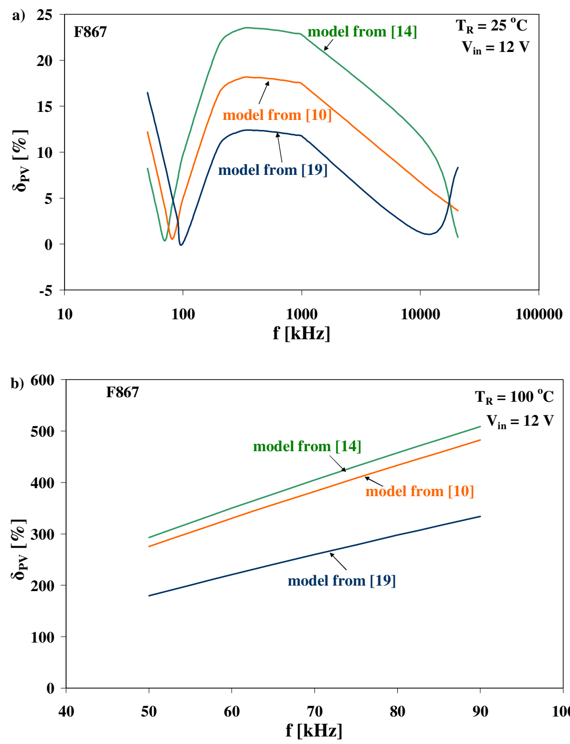

Fig. 8. The dependence of the power losses error in the ferromagnetic inductor core on frequency at Vin = 12 V for the core temperature equal to a) 25 ° C and b) 100 ° C, respectively.

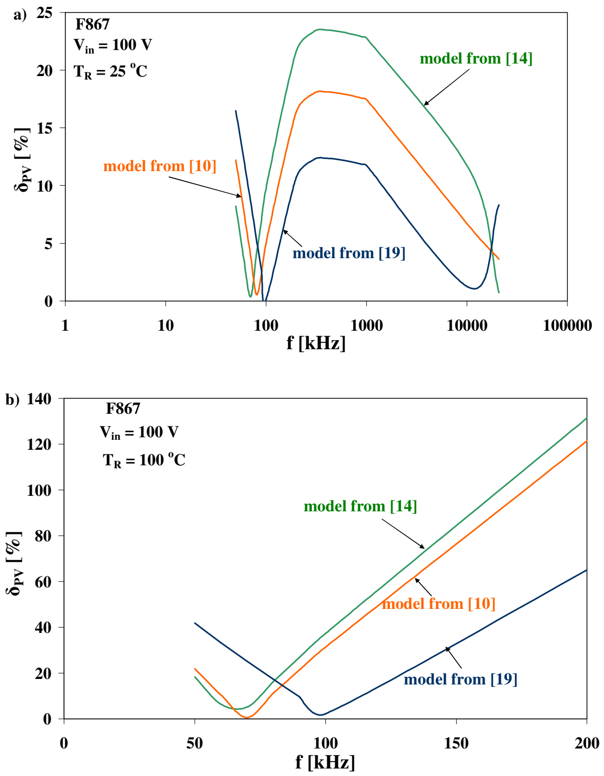

Fig. 9. The dependence of the power losses error in the ferromagnetic inductor core on frequency V_{in} = 100 V for the core temperature equal to a) 25 ° C and b) 100 ° C, respectively.

V. Conclusions

The paper presents the results of calculations obtained using the literature models and the authors' models to calculate power losses in magnetic materials used to build cores operating in the boost converter. The investigations were carried out for ferrite material F867 assuming that magnetic flux density has a sinusoidal waveform and using a circuit of boost converter in which the magnetic flux density is a triangular waveform. The obtained results of calculations show that in order to determine power losses of the inductor core it is very important to take into account the waveform of magnetic flux density and the influence of temperature and frequency on properties of magnetic materials. Omission of the influence of the mentioned parameters may cause an increase of power losses in the core of the inductor exceeding even 75%.

In addition, the use of the classical Steinmetz model to calculate power losses in magnetic materials is justified in the range of frequency not exceeding 25 kHz. Above this frequency, an increase in power losses in magnetic material per unit volume by up to 15% is observed.

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