Investigations of the influence of frequency on power losses in ferrite cores

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Abstract. In the paper the problem of the influence of frequency on power losses in ferrite cores is considered. The method of measurements of these losses is proposed. This method is realized when direct current flows in three steps. The first of them is the measurement of the core thermal resistance in this core. Next, mutual thermal resistance between the winding and the core is measured. In the third step temperature of the inductor containing the considered core operating in a boost converter is measured at the steady state with an optical method. The power dissipated in the core is calculated using the formula elaborated by the Authors. Some results of measurements of the inductor containing ferrite cores of different dimensions are presented and discussed.

1. Introduction
Magnetic elements are important components of switch-mode power supplies [1]. Properties of these elements strongly depend on phenomena occurring in ferromagnetic cores [2, 3, 4]. Such cores may be made of different magnetic materials, but in the range of high frequency ferrites are particularly used [2].

The range of applications of each magnetic element determines, among others, power losses in the core. In accordance with the commonly used Steinmetz formula, power losses in the ferromagnetic core increase proportionally to frequency, which is raised with the exponent higher than 1 [2, 5, 6]. However, as it is clear from the literature [7, 8, 9, 10, 11] experimental investigations of the influence of frequency on power losses in magnetic materials are carried out only in the range of frequency not higher than several kHz. The values of power losses in the core given in the catalogue data for higher frequency are the effect of extrapolation of the measurement results using the Steinmetz formula. Higher values of frequency are taken into account in the papers [7, 12, 13, 14, 15], only.

The safe operating area of magnetic elements is limited e.g. by thermal phenomena, which cause an increase in the internal temperature of these elements. Typically, compact thermal models of magnetic devices are used [12, 13], in which uniform temperature distribution in the considered device is assumed. In such models thermal properties of the considered elements at the steady state are characterized by thermal resistance.

In the literature, e.g. [12, 16] electrothermal models of magnetic elements (inductors and transformers) that make it possible to calculate the internal temperature of the core during operation of these elements are presented. In many of the considered papers the Steinmetz formula is used to calculate power losses in ferromagnetic cores [17]. Unfortunately, this formula is elaborated for the
dissipated power of the shape of a sinusoidal waveform only. Modifications of this formula are proposed e.g. in [2, 6, 13]. If magnetic elements operate in switch-mode power supplies, the waveforms of currents, voltages and power dissipated in the cores considerably differ from sinusoidal waveforms. Therefore, the problem of estimating the average value of this power occurs.

Correct modelling of properties of magnetic elements at high frequencies requires a reliable description of the influence of significant factors on power losses in the core made of magnetic materials, which can be used in devices operating at high frequencies up to several MHz. Obtaining such a description requires performance of experimental investigations, which will illustrate the influence of frequency on power losses in the core made of magnetic material [14].

The paper presents a method of measuring power losses in the ferrite core and the results of measurements of the selected pot cores of different dimensions. These results show the influence of frequency on power losses in the core used in an inductor included in the boost dc-dc converter.

In Section 2 the used measurement method is described, whereas the results of investigations are presented in Section 3.

2. Measurement method

The applied measuring method is an extension of the method described in [14] and it assumes that thermal properties of the core do not depend on the dissipated power in the core or frequency. Measurements are carried out in three stages, and the tested element is an inductor containing the considered ferrite core.

First, the dependence of temperature of the dissipated power in the core while feeding the core with the DC flowing through the core is measured. The value of this current is adjusted by the voltage source $V_{in}$ and the resistor $R$. The temperature of the core is measured with the use of a pyrometer and power losses in the core are equal to multiplication of the current flowing through it (measured by an ammeter) and the voltage on the core (measured by a voltmeter). The measurement set-up indispensable for these measurements is shown in Fig.1.

![Figure 1](image_url)

**Figure 1.** The measurement set-up used in the first step of the method.

The current value is changed in wide ranges to obtain visible changes in the core temperature as a result of a selfheating phenomenon. On the basis of the results of measurements thermal resistance of the core $R_{th}$ is calculated and it is equal to the quotient of an increase of the core temperature $T_B$ at the steady state above the ambient temperature $T_a$ by the power dissipated in the core $P_R$.

In the second step through the winding of the inductor the direct current with the adjustable value (adjusted by the voltage source $V_{in}$ and the resistor $R$) flows and the core temperature is measured with the pyrometer and the voltage on the winding and the current winding are measured, too, using the voltmeter and the ammeter, respectively. The measurement set-up used in this step of measurements is shown in Fig. 2.

An increase of the core temperature over the ambient temperature is caused by mutual thermal interaction between the winding and the core. The winding current is regulated in a wide range, which causes changes in the value of the core temperature up to tens of Celsius degrees. On the basis of the
results of measurements mutual thermal resistance between the windings and the core $R_{thUR}$ is calculated and it is equal to the quotient of an increase in the core temperature $T_R$ at the steady state above the ambient temperature $T_a$ by the power dissipated in the winding $P_U$. This power is equal to the product of current and voltage measured by the voltmeter and the ammeter, respectively.

![Figure 2](image-url)

**Figure 2.** The measurement set-up used in the second step of the method.

In the third step the inductor including the investigated core and the winding used in the second step of the method is mounted in the boost dc-dc converter. During measurements, this converter should operate in the discontinuous conducting mode in order to obtain the highest maximum value of the inductor voltage. The maximum value of flux density $B_m$ in the core is proportional to this voltage. At the high value of $B_m$ a high value of the power dissipated in the core could be obtained. Through the winding the alternating current with adjustable maximum value and frequency flows. The measurement set-up used in this step is shown in Fig. 3.

![Figure 3](image-url)

**Figure 3.** The measurement set-up used in the third step of the method.

The value of the core temperature at the steady state is measured with the pyrometer. Current and voltage of the winding are also measured. In this case, an increase of the core temperature $T_R$ is caused by selfheating in the core characterized by thermal resistance of the core $R_{thR}$ and mutual thermal coupling between the winding and the core characterized by mutual thermal resistance between the winding and the core $R_{thUR}$. A loss of power is a result of its remagnetization and by thermal coupling between the winding and the core, when in the winding the power is dissipated due to the flow of the alternating current. For each of the considered conditions of the winding supply, the average values of power losses in the core at the steady state are calculated using the formula

$$P_R = \frac{T_R - T_a - R_{thUR} \cdot P_U}{R_{thR}}$$

(1)
where $T_a$ – the ambient temperature, $p_U$ – the average value of power losses in the core.

The proposed measurement method has some disadvantages, which limit accuracy of this method. As it was proved e.g. in [18] the thermal resistance of the core is not constant, but it is a decreasing function of the power dissipated in it. Losses in the winding caused by eddy currents are omitted. The influence of the speed of air flow and dimensions of sweet steel on thermal resistance of the core are not taken into account. Simplification assumed at the formulation of the presented measurement method does not significantly influence the accuracy of this method.

### 3. Results of investigations

The experimental investigations were carried out for inductors with two pot ferrite cores (shown in Fig. 4) of the diameter equal to 30 mm and the height equal to 19 mm (big core) and of the diameter equal to 18 mm and the height equal to 11 mm (small core) made of ferrite material F-2001. The big core was investigated for inductors with three types of windings including different numbers of turns: 54, 5 and 2. The power supply was provided to the investigated pot cores by means of connectors made of sweet steel tightened to the bases of the pot with screws. These windings are made of copper wire enamel of the diameter equal to 0.8 mm. The winding of the investigated inductor with the small core contains 2 and 5 turns of copper wire with the same diameter. Measurements of the core temperature were performed using the pyrometer Optex PT-3S with resolution of 0.1 °C.

![Figure 4](image)

**Figure 4.** Views of the investigated cores: a) the big core, b) and the small core.

Figure 5 shows the measured dependence of the big core (Fig. 5a) and the small core (Fig. 5b) temperature on the current flowing through the core during the first step of measurements on the power dissipated in the core during the first step of the measurement method. In Fig 5a blue and red lines denote the number of winding turns equal to 54 and 2, respectively, whereas in Fig. 5b – 2 and 5 turns, respectively.

![Figure 5](image)

**Figure 5.** The measured dependence of the core temperature on the power dissipated in the big core (a) and the small core (b).
As can be seen, the considered dependence for both the considered cores is almost linear, which proves that thermal resistance of the core does not depend on the power dissipated in the core. It is worth noticing that the number of turns influences thermal resistance of the core $R_{thUR}$. Particularly, for the small core changing this number from 2 to 5 turns causes an increase in the value of $R_{thUR}$ even by 15%. Probably, the observed phenomenon is a result of worsening of the heat convection process, when the winding fills the interior of the core [19]. Such a dependence is difficult to observe for the big core. In turn, it is worth noticing that thermal resistance of the big core is twice as low as the small core. This is a result e.g. of different surface area, at which heat convection occurs.

In turn, in Fig. 6a and Fig. 6b dependences of the core temperature on the power dissipated in the winding for the big core and the small core are shown.

![Figure 6](image)

**Figure 6.** The measured dependence of the core temperature on the power dissipated in the winding of the big core (a) and the small core (b).

As can be seen, the considered dependence for both the considered cores is almost linear. The measured values of mutual thermal resistance between the windings and the core $R_{thUR}$ are smaller than thermal resistance of the core $R_{thUR}$ even twice. For the big core and the small value of turns ($z = 2$) measurements were conducted for the power $P_U$ smaller than 0.6 W due to the small value of resistance of this winding and the limited value of the output current of the used power supply. For the small core, the strong influence of the number of turns on the value of $R_{thUR}$ is visible. In the case when $z = 5$ this value is even by 40% higher than in the case when $z = 2$.

In Figure 7 the dependence of power losses in the big core (Fig. 7a) and the small core (Fig. 7b) of the considered inductor operating in the boost converter on frequency of the control signal is presented. This converter operates at the input voltage equal to 6.75 V and load resistance equal to 1 kΩ.

![Figure 7](image)

**Figure 7.** The dependence of power losses in the big core (a) and the small core (b) on frequency.

As it is visible, power losses in the core are a decreasing function of frequency. This shape of the considered dependence is a result of a decreasing dependence of the amplitude of flux density on frequency. As it is presented e.g. in the papers [6, 13, 15] the exponent in the dependence of core
losses on flux density amplitude is higher than the exponent in the dependence of this power on frequency. On the basis of the obtained values of the power dissipated in the core and the measured values of $R_{th}$, it is possible to calculate an excess of the core temperature over the ambient temperature caused by self-heating phenomena in the core. This excess can be higher than 20°C.

The power dissipated in the core of an inductor operating in the boost converter depends e.g. on frequency and the input voltage of this converter. In Fig. 8 the influence of frequency on the dependence of the power dissipated in the core on the converter input voltage is illustrated. Both the investigated inductors contain windings with 5 turns.

As it is visible, for both the considered cores the power dissipated in these cores is an increasing function of the converter input voltage. For the big core an increase of power $P_R$ while increasing frequency is observed. In turn, for the small core it is visible, that the dependence of power $P_R$ on frequency has the maximum for frequency equal to about 40 kHz. For the big core higher values of power $P_R$ were obtained.

![Figure 8](image_url)

**Figure 8.** The dependence of power losses in the big core (a) and the small core (b) on the converter input voltage.

4. Conclusions

In the paper the method to measure power losses in ferrite cores used to build inductors is proposed. The proposed method is based on the dependence of the temperature of the core on the power dissipated in the core and the winding. This method was used to measure power losses in the selected pot cores at a wide range of frequency of the current flowing through the winding.

The obtained results of investigations prove that the power dissipated in the core included in the inductor operating in the boost converter is a decreasing function of frequency (for frequency higher than 40 kHz) and an increasing function of the input voltage of the boost converter. An increase of the core temperature caused by self-heating in the core is higher for the big core than for the small core and it can exceed even 20°C. The power $P_R$ can be high if the considered converter operates with the high value of load resistance, because in this case the converter operates in the DCM mode and the amplitude of flux density could have a high value.

The presented results could be useful for designers of switch-mode power supplies. Applications of the considered method of estimation of the average value of power dissipated in the core could make it easier estimation of the core operating temperature and verification, if the core functions in its safe operating area.

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