Article

Influence of Power Losses in the Inductor Core on Characteristics of Selected DC–DC Converters

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Abstract: The paper presents the results of a computer simulation illustrating the influence of power losses in the core of an inductor based on the characteristics of buck and boost converters. In the computations, the authors’ model of power losses in the core is used. Correctness of this model is verified experimentally for three different magnetic materials. Computations are performed with the use of this model and the Excel software for inductors including cores made of ferrite, powdered iron, and nanocrystalline material in a wide range of load resistance, as well as input voltage of both the considered converters operating at different values of switching frequency. The obtained computation results show that power losses in the inductor core and watt-hour efficiency of converters strongly depend on the material used to make this core, in addition to the input voltage and parameters of the control signal and load resistance of the considered converters. The obtained results of watt-hour efficiency of the considered direct current (DC)–DC converters show that it changes up to 30 times in the considered ranges of the mentioned factors. In turn, in the same operating conditions, values of power losses in the considered cores change from a fraction of a watt to tens of watts. The paper also considers the issue of which material should be used to construct the inductor core in order to obtain the highest value of watt-hour efficiency at selected operation conditions of the considered converters.

Keywords: DC–DC converters; ferromagnetic cores; modeling; power losses

1. Introduction

Direct current (DC)–DC converters, which are used, e.g., in switch mode power supplies and semiconductor devices, also contain magnetic elements used to store electrical energy [1]. In recent years, more and more papers focused on modeling power losses in magnetic elements and on examining the influence of power losses in these elements on the characteristics of electronic equipment [1–12].

The aspiration to minimize the sizes of power supplies and to increase the frequency of the control signal causes an increase in power loss density in ferromagnetic cores and, consequently, limits the watt-hour efficiency of DC–DC converters [2,8–10,12]. Losses in magnetic material can be caused, e.g., by hysteresis of the magnetizing curve or by eddy currents [13]. Values of power loss components depend on many factors, e.g., the type of magnetic material used, the amplitude and frequency of the waveforms of magnetic flux density, and their shape [5,13–20].

In previous studies [13,16–19], the methods for computing power losses in magnetic materials based on modifications of the Steinmetz model, defined as improved Steinmetz equation (ISE) or modified Steinmetz equation (MSE), were presented. In these models, the shape of the waveform of the excitation signal is taken into account; however, the influence of temperature on the properties of magnetic materials and on the parameters of the considered model is not taken into account. Yet, in the presented research results, among others, ferrite materials such as N87 were used, whose properties...
strongly depend on temperature. In addition, as stated in the cited papers, these models are valid only for a low value of frequency up to 20 kHz.

In turn, in Reference [15], a new model called I2SE was proposed. This model is an extended version of the ISE model. In this model, five additional parameters related to the relaxation process are added. However, the mentioned model also does not take into account the influence of temperature on the properties of magnetic materials and their power loss. Additionally, the presented description does not allow its implementation in the SPICE software. In Reference [5], three models of a ferromagnetic core were proposed. The first was a linear model, the second was a non-linear isothermal model that uses the classic Jiles–Atherton model to describe the magnetization curve, and the third was an electrothermal model of the ferromagnetic core. The electrothermal model took into account influence of temperature on core properties, but unfortunately contained a formal error, which did not allow computing power losses based on the magnetization curve obtained from this model.

Reference [12] presented a method of modeling power losses in the core of the inductor, which is a component of the boost converter. The results of computations using the various models described, among others [13,16,17,19], were compared to the results obtained using the authors’ model given in Reference [3], which took into account the influence of temperature, frequency, and the shape of magnetic flux density on the properties of magnetic materials and power losses in the ferromagnetic core of an inductor.

In References [2,14,21,22], much emphasis was given to the analysis of the influence of losses in semiconductor devices on the characteristics of DC–DC converters. Yet, losses in the cores of magnetic elements were omitted in these analyses. The problem of the influence of models of power losses in ferromagnetic cores on the characteristics of buck and boost converters was also considered in References [13,20]. In the cited papers, it was shown that the use of classical models described References [14,23] can cause significant underestimation of power losses in the core. The observed changes in the values of power losses can increase three-fold. In addition, most of the presented models are based on a linear approximation of the real characteristics of inductors or transformers. Such an approach may cause overstated or understated watt-hour efficiency of electronic circuits [19,24,25].

On the other hand, in Reference [26], the average electrothermal model of an inductor was described; it took into account the dependence of power losses in ferromagnetic materials on frequency and temperature. The investigations were carried out for the boost converter. Reference [27] presented the results of computations for the boost converter using the electrothermal model of an inductor and hybrid models of diodes and transistors.

The aim of this paper was to analyze the influence of power losses in the inductor core on the characteristics of selected DC–DC converters. Investigations are performed for buck and boost converters including inductors with cores made of different ferromagnetic materials. The authors’ model of losses in the ferromagnetic core is used in computations performed with the use of the Excel software. The dependences of power losses in the inductor core and watt-hour efficiency of the considered DC–DC converters on load resistance, input voltage, and switching frequency are computed. The influence of selection of the material used to make the inductor core on the properties of the considered converters is discussed.

In Section 2, the Steinmetz, the natural Steinmetz, and the authors’ models of power losses occurring in magnetic materials are described. Section 3 presents the investigated converters, while Section 4 outlines the results of computations obtained using the chosen models.

2. Model of Power Losses in the Core of an Inductor

In the literature, many papers focusing on power losses per unit of volume (\(P_V\)) in magnetic materials proposed power loss models of the inductor core. Unfortunately, some models did not have the analytical dependence describing losses in the ferromagnetic core. This makes it impossible to implement these models in an easy way using computer programs. Many models were described in References [12,20]; however, they concerned models of power losses in magnetic materials which took
into account the triangular shape of amplitude of magnetic flux density in the core. The Steinmetz model \[23\] was also considered in these papers as the first model of power losses in magnetic materials, shown below.

\[
P_{\text{loss}} = k \cdot f^\alpha \cdot B_m^\beta, \tag{1}
\]

where \(k\), \(\alpha\), and \(\beta\) are material parameters, \(B_m\) is the amplitude of magnetic flux density, and \(f\) is the frequency.

The results given in Reference \[20\] showed that differences between values of power dissipated in the inductor core computed with the use of the models described in References \[13,23\] and the catalog data reached as high as 60%. In contrast, the results of computations performed with the use of the core model described in Reference \[3\] adequately fit the catalog data. In practice, this means that the use of classical models to describe power losses in the core, given in References \[13,23\] makes it impossible to obtain correctly computed values of power losses. Differences between the values obtained with the authors’ model given in Reference \[3\] and the considered literature models are largest at high values of temperature, frequency of the control signal, and input voltage \[20\]. In turn, the results given in Reference \[12\] showed that, in order to compute power losses of the inductor core included in the boost converter, it is essential to take into account the shape of the waveform of magnetic flux density and the influence of temperature and frequency on the properties of magnetic materials. Omitting the influence of the mentioned factors could cause overestimation of power losses in the core of an inductor, exceeding even 75% \[12\].

In addition, the use of the classical Steinmetz model \[23\] to compute power losses in magnetic materials is justified in the range of low frequency not exceeding 25 kHz \[12\]. For frequency values higher than 25 kHz, power losses in the magnetic material per unit volume increase by up to 15% \[3,12\].

In Reference \[28\], it was shown that the total power losses in the toroidal core of a transformer are the sum of hysteresis losses and eddy current losses. The eddy current losses are computed on the basis of Equation (2).

\[
P_w = \frac{\pi}{6} \cdot \sigma_f \cdot dd^2 \cdot B_m^2 \cdot f^2, \tag{2}
\]

where \(\sigma_f\) is the conductivity of the material, \(B_m\) is the amplitude of sinusoidal magnetic flux density at frequency \(f\), and \(dd\) is the thickness of the sheet.

Reference \[29\] presented the procedure for formulating a general model of power losses frequently appearing in previous models; however, the drawback of this model was the fact that it is dedicated to laminated sheets and was verified only for frequencies up to 2 kHz.

In Reference \[30\], the results of investigations on how to compute power losses in soft magnetic materials as a result of the movement of single Bloch walls during magnetization of magnetic material were presented. The well-defined domain structures of the equation with limited accuracy were additionally formulated. The conclusions presented in the cited paper allowed determining trends of power losses in different ferromagnetic materials \[3\].

For example, Reference \[13\] showed a method of modeling power losses in magnetic materials, called the natural Steinmetz extension (NSE). This method can be used for sinusoidal and triangular waveforms of magnetic flux density. In the cited paper, it was shown that the coefficients \(\alpha\), \(\beta\), and \(k_w\) of the proposed model significantly depend on frequency and temperature. Yet, no analytical dependence describing such influence was given.

In Reference \[3\], dependences describing power losses in magnetic materials which took into account the influence of temperature and frequency of \(B(t)\) on the power losses and on the parameter \(\beta\) were proposed. The formula describing power loss density has the following form \[3\]:

\[
P_v = P_v0 \cdot f^\alpha B_m^\beta \cdot (2 \cdot \pi)^\alpha \cdot \left(1 + \alpha_p \cdot (T_R - T_m)^2\right) \cdot (0.6336 - 0.1892 \cdot ln(\alpha)) \tag{3}
\]
where $\alpha_p$ is the temperature coefficient of losses in ferromagnetic material, $T_R$ is the core temperature, $T_m$ is the temperature at which the material has the smallest loss, and parameter $P_{v0}$ is described by Equation (4) [3].

$$P_{v0} = a \cdot \exp\left(-\frac{f + f_0}{f_3}\right) + a_1 \cdot (T_R - T_m) + a_2 \cdot \exp\left(-\frac{f - f_2}{f_1}\right),$$

(4)

where $a, a_1, f_0, f_1, f_2,$ and $f_3$ are material parameters.

In turn, parameter $\beta$ is described by Equation (5) [3].

$$\beta = \begin{cases} 2 \cdot (1 - \exp(-T_R/\alpha_T)) + 1.5 \cdot \left(\begin{array}{c} f_1 \\ f_2 \\ f_3 \end{array}\right) & \text{if } 1 - \exp(-T_R/\alpha_T) > 0 \\ 1.5 & \text{if } 1 - \exp(-T_R/\alpha_T) < 0 \end{cases}$$

(5)

where $\alpha_T$ is a material parameter.

For the triangular waveform of magnetic flux density, power losses in magnetic material can be computed from the dependence shown in Equation (6) [3].

$$P_V = P_{v0} \cdot \left(\alpha_p B_m\right)^2 \cdot 2^\alpha \cdot \left(1 + \alpha_p \cdot (T_R - T_m)^2\right) \cdot \left(d^{1-\alpha} + (1 - d)^{1-\alpha}\right),$$

(6)

where $d$ denotes the duty factor of the triangular waveform.

In Table 1, model parameter values for the core model from Reference [3] for selected magnetic materials are shown. The investigations were carried out for inductors containing cores made of powdered iron (RTP), ferrite material (RTF), and nanocrystalline material (RTN).

### Table 1. Model parameters values of selected inductor core RTP—powdered iron; RTF—ferrite material; RTN—nanocrystalline material.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RTP</th>
<th>RTF</th>
<th>RTN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1.15</td>
<td>1.29</td>
<td>1.88</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>0</td>
<td>0.00011</td>
<td>0</td>
</tr>
<tr>
<td>$T_m$ (K)</td>
<td>368</td>
<td>343</td>
<td>358</td>
</tr>
<tr>
<td>$a$</td>
<td>10</td>
<td>1.1</td>
<td>100</td>
</tr>
<tr>
<td>$f_0$ (Hz)</td>
<td>2000</td>
<td>25,000</td>
<td>200</td>
</tr>
<tr>
<td>$f_1$ (kHz)</td>
<td>90</td>
<td>1,000,000</td>
<td>300</td>
</tr>
<tr>
<td>$f_2$ (Hz)</td>
<td>10</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>$f_3$ (Hz)</td>
<td>15,000</td>
<td>50,000</td>
<td>10</td>
</tr>
<tr>
<td>$a_1$</td>
<td>10</td>
<td>0.013</td>
<td>0.01</td>
</tr>
<tr>
<td>$a_2$</td>
<td>12</td>
<td>0.7</td>
<td>0.00019</td>
</tr>
</tbody>
</table>

The method of estimating the parameter values of the authors’ model given in Reference [3] was described in detail in Reference [31], while material parameters ($\alpha$) of the Steinmetz model described in Reference [23] had the same values as for the model parameters presented in Reference [3], and parameters $k$ and $\beta$ were computed using the transformed Equation (1) with the catalog data of power losses per unit volume ($P_v$) in magnetic material at a specific value of frequency ($f$) and amplitude of magnetic flux density ($B_m$).

Figure 1 shows the dependence of power loss density in ferrite material (RTF) for two core temperatures equal to 25 °C (a) and 100 °C (b) in a wide range of frequency changes. In Figures 1–3, points denote the catalog data [32], the solid lines denote the results of computations obtained using the model from Reference [3] described by Equations (3)–(5), and the dashed lines denote the results of computations using the model from Reference [23] described by Equation (1).
As can be seen in Figure 1, with an increase in frequency, power losses in the magnetic material increase at a different value of amplitude of magnetic flux density. It is also worth noting that good agreement between the catalog data [33] and the results of computations performed with the use of the model given in Reference [3] was obtained.

Figure 2 shows the dependence of power loss density in nanocrystalline material (RTN) on the frequency at three values of amplitude of magnetic flux density equal to 150, 300, and 600 mT. As can be seen, power losses in the nanocrystalline material increase with an increase in frequency. Also, good agreement between the catalog data [33] and the results of computations performed with the use of the model from Reference [3] was obtained.

Figure 3 presents the dependence of power losses per unit volume ($P_v$) in the inductor core made of powdered iron (RTP) material on the frequency. As can be seen, as for cores made of the other considered materials (RTN, RTF), power losses per unit of volume increase with an increase in frequency. As can be seen, power losses in the nanocrystalline material increase with an increase in frequency. Also, good agreement between the catalog data [33] and the results of computations performed with the use of the model from Reference [3] was obtained.

As can be seen in Figure 1, with an increase in frequency, power losses in the magnetic material increase at a different value of amplitude of magnetic flux density. It is also worth noting that good agreement between the catalog data and computations made with the use of the model given in Reference [3] was obtained for both considered values of temperature.

Figure 2. Dependence of power losses per unit volume ($P_v$) in the core made of nanocrystalline material (RTN) on the frequency.

Figure 3. Dependence of power losses per unit volume ($P_v$) in the inductor core made of powdered iron material (RTP) on the frequency.
frequency, also leading to good agreement between the catalog data and the results of computations performed with the use of the model from Reference [3].

The results presented in Figures 1–3 show that the authors’ model ensures good agreement between the computed and catalog dependences of power losses on frequency, amplitude of magnetic flux density, and temperature. In turn, the Steinmetz model gives the value of these losses even several times higher. Differences between the results of computations made using both the considered models are particularly high for the ferrite core (F867). For the core made of powdered iron (−26), the results obtained with both the models are practically identical. For the nanocrystalline core (RTN), the computed values of power loss using the Steinmetz model are lower than the values of power loss using the authors’ model and the catalog data in the range of high frequency.

In order to compute power losses in the inductor core, it is necessary to multiply losses expressed with Equations (1), (3), and (6) by the equivalent volume of the core ($V_e$).

As mentioned earlier, omission of the dependence of power losses in the magnetic material on the frequency, temperature, and the shape of magnetic flux density can cause a significant overstatement of power losses in the inductor core. As shown in Reference [20], a significant effect on power losses in magnetic materials results from the shape of the magnetic flux density $B(t)$ waveform. The data provided by the manufacturers usually refer to the case when the waveform of magnetic flux density $B(t)$ is sinusoidal. The ferromagnetic core, being a component of such magnetic elements as an inductor, is generally used in systems in which the waveform of magnetic flux density is triangular. Therefore, in order to determine the influence of power losses on the characteristics of the buck and boost converter, computations were carried out taking into account the triangular waveform of magnetic flux density, and power losses in the inductor core were computed from the dependence in Equation (6). As can be seen from the dependence in Equation (6), power losses in the core of an inductor operating in a DC–DC converter depend on the frequency, amplitude of magnetic flux density, and duty factor of the signal controlling the transistor.

### 3. Investigated Converters

In order to investigate the influence of power losses in the inductor core on the properties of selected DC–DC converters, computations were performed for the boost converter and the buck converters, whose electrical diagrams are shown in Figure 4.

![Diagrams of the boost (a) and the buck (b) converters.](image)

In the tested converters, the diode and the transistor are modeled as ideal switches. In this case, power losses are dissipated in inductor $L$ only. In order to compute such losses in magnetic materials, the value of amplitude of magnetic flux density should be computed using the following formula $[12,22]$

$$B_m = \frac{L \cdot \Delta I_L}{2 \cdot S_F},$$

where $S_F$ denotes the cross-section area of the core, $z$ is the number of turns, and $\Delta I_L$ is the peak-to-peak value of inductor current. In the boost converter, the value of $\Delta I_L$ is computed with the following formula $[12,22]$

$$\Delta I_L = \frac{V_{in} \cdot d \cdot T}{L}.$$
where \( V_{in} \) is the value of input voltage of the boost converter.

In turn, the peak-to-peak value of inductor current \( \Delta I_L \) for the buck converter is computed with the following formula \([12,22]\):

\[
\Delta I_L = \frac{(V_{in} - V_{out}) \cdot d \cdot T}{L}.
\]  

(9)

As resulting from Equation (7), the value of amplitude of magnetic flux density is a function of the number of turns, inductance, cross-section area of the core, input voltage of the converter, the duty cycle, and the period of switching. It is important that the converter operation mode does not influence the formula describing power losses of the inductor core.

For the boost converter operating in continuous conducting mode (CCM), the value of the output voltage depends only on input voltage and the control signal duty cycle, and it is described as follows:

\[
V_{out} = V_{in} \cdot \frac{1}{1 - d}.
\]  

(10)

On the other hand, for the boost converter operating in discontinuous conducting mode (DCM), the converter output voltage is described as follows \([21]\):

\[
V_{out} = V_{in} \left[ 1 + \frac{V_{in} \cdot d \cdot T \cdot R_0}{2 \cdot L \cdot V_{out}} \right].
\]  

(11)

The boost converter operates in CCM mode if the following formula is fulfilled:

\[
R_0 \geq \frac{2 \cdot L \cdot V_{out}}{V_{in} \cdot (1 - d) \cdot d \cdot T}.
\]  

(12)

In turn, output voltage of the buck converter operating in CCM mode for a given input voltage \((V_{in})\) and duty cycle of the control signal \((d)\) is described in Equation (13) \([22]\).

\[
V_{out} = d \cdot V_{in}.
\]  

(13)

Output voltage of the buck converter operating in DCM mode is given in Equation (14) \([22]\),

\[
V_{out} = \frac{V_{in}}{\frac{2 \cdot k_0 L}{V_m} + 1},
\]  

(14)

and depends on inductance of inductor \(L\), output current \(I_0\), and the period of the control signal \(T\).

The buck converter operates in DCM mode when the following dependence is fulfilled:

\[
R_0 \geq \frac{2 \cdot L}{(1 - d) \cdot T}.
\]  

(15)

4. Results of Computations

In order to verify the influence of power losses in the inductor core on selected DC–DC converters, computations using the model presented in Reference [3] and described by Equations (3)–(6) were performed with the Excel software. The accuracy of the calculations is limited by the accuracy of the used models of power losses in the inductor core and by the model DC–DC converter characteristics.

As a further consideration, the model of inductor core losses from Reference [3] was chosen because, as can be seen in Figures 1–3, it correctly models the losses in magnetic materials. In addition, the selected model takes into account the triangular waveform of magnetic flux density. In the considerations, it is assumed that inductance of the inductor is constant for all the considered materials as a result of the air gap occurring in the core in a given range of changes of the magnetic field, as shown in Figure 5 \([34]\). Investigations were carried out for ring cores made of ferrite (RTF), powdered iron
(RTP), and nanocrystalline material (RTN) [31–33,35]. In order to emphasize the influence of power losses on the characteristics of the considered circuits, inductor cores of large size were chosen for testing. The company Ferryster [35] offers toroidal cores with the outside diameter of the considered cores equal to 102 mm, the internal diameter equal to 57.3 mm, and the height equal to 33 mm. In the computations, each of the considered cores had identical size, and, due to differences in the length of the air gap, each inductor had the same inductance \( L = 100 \, \mu \text{H} \), while 27 winding turns and a cross-section area \( S_{T} \) of 737.55 mm\(^2\) were adopted.

![Figure 5. Typical dependence of magnetic permeability on magnetic force [34].](image)

In order to compute the value of magnetic flux density, the dependence in Equation (7) was used assuming inductance \( L \) as constant. The peak-to-peak current value \( \Delta I_{L} \) was computed using the dependence in Equation (8) for the boost converter and the dependence in Equation (9) for the buck converter.

Figure 6 presents the dependence of the amplitude of magnetic flux density on the input voltage of the boost converter (Figure 6a) and the buck converter (Figure 6b). In order to compute the value of amplitude of magnetic flux density, Equation (7) was used. All the presented characteristics in this section were determined on the assumption that the duty cycle was equal to 0.5.

![Figure 6. Dependence of the amplitude of magnetic flux density on the input voltage of the boost converter (a) and the buck converter (b).](image)

As shown in Figure 6, the dependence of amplitude of magnetic flux increases linearly with an increase in input voltage, obtaining values up to 350 mT for the boost converter and 180 mT for the buck converter at an input voltage equal to 100 V.

Later in this section, ferromagnetic cores used in the inductor contained in the considered converters are denoted with as follows: powder iron core (-26, RTP), nanocrystalline core (M070, RTN), and ferrite core (F867, RTF).

Figures 7–9 present the influence of input voltage \( V_{\text{IN}} \), control signal frequency, and load resistance of the boost converter on power losses in the inductor core and the watt-hour efficiency of the converter.
for three considered materials used to build the inductor core (i.e., RTP, RTF, and RTN). Values of watt-hour efficiency were computed as follows:

$$\eta = 1 - \frac{P_R \cdot R_0}{V_{\text{out}}^2}$$  \hspace{1cm} (16)

where $P_R$ denotes power losses in the inductor core computed using Equations (4)–(6).

**Figure 7.** Dependence of power losses in the inductor core (a) and watt-hour efficiency of the boost converter (b) on input voltage.

**Figure 8.** Dependence of power losses in the inductor core (a) and watt-hour efficiency of the boost converter (b) on frequency of the control signal.

**Figure 9.** Dependence of the watt-hour efficiency of the boost converter on the load resistance.

Figure 7 presents the influence of input voltage on power losses in the inductor core and the watt-hour efficiency of the boost converter.

Dependences of power losses in the inductor core and the watt-hour efficiency as a function of input voltage of the considered converters presented in Figures 7 and 8, and in Figures 10 and 11 were computed using Equations (6) and (16), respectively.
power losses in the inductor core for all the considered materials. However, the highest value of these power losses was obtained for the inductor containing the core made of nanocrystalline material (about 500 W at $V_{\text{in}} = 100$ V), while the lowest value of these power losses was obtained for the ferrite core (120 W at $V_{\text{in}} = 100$ V).

In turn, watt-hour efficiency was highest for the inductor containing the core made of ferrite material in the whole considered range of input voltage ($\eta \geq 0.9$), and the lowest value of watt-hour efficiency was obtained for the inductor containing the nanocrystalline core. It is worth noting that, for the range of input voltage from 10 to 40 V, the watt-hour efficiency of the converter containing an inductor with the nanocrystalline core decreased from 0.9 to 0.65.

Figure 8 presents the influence of the control signal frequency on power losses in the inductor core and the watt-hour efficiency of the boost converter.
The dependence of power losses in the inductor core made of ferrite (RTF) and powdered iron (RTP) decreased with an increase in frequency. In the considered range of frequency for the RTP core, power losses decreased from 86 W to 16 W, whereas, for the RTF core, they decreased from 32 W to 3 W. In turn, for the core made of nanocrystalline material, the considered dependence was a monotonically increasing function, and power losses increased from 12 W to 39 W. The highest power losses in the core were observed at \( f = 50 \) kHz (87 W for RTP), whereas, at frequency \( f = 500 \) kHz, this power was equal to 41 W for RTN. In turn, the watt-hour efficiency of the boost converter was an increasing function of frequency for the inductor containing RTF or RTP cores, whereas this efficiency was a decreasing function of frequency for the inductor containing the RTN core. The highest watt-hour efficiency equal to 0.98 was obtained for the converter containing an inductor with the RTF core at frequency \( f > 250 \) kHz, whereas, for this converter containing the inductor with the RTP core, the highest value of watt-hour efficiency was equal to 0.92. In turn, the watt-hour efficiency of the boost converter with the inductor including the RTN core decreased in the considered range of frequency from 0.97 to 0.84.

Figure 9 presents the influence of load resistance on the watt-hour efficiency of the boost converter. Due to the constant value of amplitude of magnetic flux density and frequency, values of power losses for the boost converter in the load resistance function were constant and amounted to 73 W for the RTP core, 24 W for the RTF core, and 10 W for the RTN core. Therefore, only the dependence of watt-hour efficiency as a function of load resistance is presented.

The watt-hour efficiency was a decreasing function of load resistance for all the considered materials. While load resistance increased, watt hour efficiency decreased from 0.98 to 0.89 for the RTN core, from 0.91 to 0.73 for the RTF core, and from 0.79 to 0.03 for the RTP core. As shown in the figures, the lowest value of watt-hour efficiency equal to 0.03 was obtained for the RTP core.

Figures 10–12 present the influence of input voltage \( V_{\text{in}} \), the control signal frequency \( f \), and load resistance \( R_0 \) of the buck converter on power losses in the inductor core and the watt-hour efficiency of the buck converter for the three considered materials used to build the inductor core (i.e., RTP, RTF, and RTN).

![Figure 12](image)

**Figure 12.** Dependence of power losses in the inductor core (a) and watt-hour efficiency of the buck converter (b) on load resistance.

As shown in Figure 10, an increase in input voltage of the buck converter caused an increase in power losses in the inductor core for all the considered materials. However, the highest value of power losses in the inductor core was obtained for the inductor containing the RTP core (up to 87 W at \( V_{\text{in}} = 100 \) V), while the lowest value of power losses in the inductor core was obtained for the RTN core (about 10 W at \( V_{\text{in}} = 100 \) V). For the inductor core, the value of power obtained for the RTF core was equal to 24 W at \( V_{\text{in}} = 100 \) V.

In turn, the watt-hour efficiency for the inductor containing the RTN core in the whole considered range of input voltage had the same value equal to 0.95. The lowest value of watt-hour efficiency was observed for the inductor containing the RTP core. For this core, \( P_R \) decreased from 0.75 to about 0.65 only. The dependence \( \eta(V_{\text{in}}) \) for the RTF core possessed the minimum equal to 0.88 at \( V_{\text{in}} = 83 \) V, whereas the highest value was equal to 0.97 at \( V_{\text{in}} \) tending to 0.
Figure 11 presents the influence of the control signal frequency on power losses in the inductor core and the watt-hour efficiency of the buck converter.

Dependences of power losses and watt-hour efficiency had similar character as the dependences describing these parameters for the boost converter. The highest power losses in the core were obtained at \( f = 50 \text{ kHz} \) for the RTP core, where losses were equal to about 20 W. These losses decreased with an increase in frequency to about 4 W at \( f = 500 \text{ kHz} \). In the considered frequency range, power losses decreased from 7 W to 2 W for the RTF core, whereas they increased from 3 W to 11 W for the RTN core.

In turn, the highest value of watt-hour efficiency was observed for the converter containing the inductor with the RTP core at \( f = 500 \text{ kHz} \). For the buck converter with the inductor including the RTP core, the watt-hour efficiency increased from 0.67 at \( f = 50 \text{ kHz} \) to 0.94 at \( f = 500 \text{ kHz} \). In turn, this efficiency decreased from 0.95 to 0.84 for the inductor with the RTN core, and from 0.92 to 0.68 for the inductor with the RTF core.

Figure 12 presents the influence of load resistance on power losses in the inductor core (Figure 12a) and the watt-hour efficiency (Figure 12b) of the buck converter.

As shown in Figure 12, power losses in the core for \( R_0 < 20 \Omega \) were constant. Above this value of load resistance, power losses decreased monotonically in the whole range of the considered load resistance changes. The highest values were obtained for the inductor containing the RTP core (decreasing from 20.7 W to 4.5 W), while intermediate values were obtained for the RTF core (decreasing from 6.5 W to 1.5 W), and the lowest values were obtained for the RTN core (decreasing from 3 W to 0.8 W).

On the other hand, the dependence of watt-hour efficiency had the local minimum equal to 0.33 for the RTP core, 0.78 for the RTF core, and 0.9 for the RTN core at a load resistance equal to 20 \( \Omega \). Above this value of load resistance, the watt-hour efficiency of the buck converter increased with an increase of load resistance. The highest value of watt-hour efficiency was obtained for the converter containing the inductor with the RTN core. The curves presented in Figure 12 had the characteristics of spline functions due to the fact that, for \( R_0 = 20 \Omega \), the considered converter operated in the critical mode, for \( R_0 < 20 \Omega \), it was characterized by the continuous conducting mode (CCM), and, for \( R_0 > 20 \Omega \), it operated in the discontinuous conducting mode (DCM).

5. Conclusions

The paper presented the results of investigations of buck and boost converters. It was shown that the authors’ model of power losses in the ferromagnetic core ensures a better match of the computed values of losses in the inductor with the catalog data for cores made of different materials. Using this model, the dependence of power losses in the inductor core on input voltage, load resistance, and switching frequency of the converters was computed. Taking into account only losses in the core of the inductor, the watt-hour efficiency of converters was computed.

It was observed that the choice of core material could significantly influence the watt-hour efficiency of both considered DC–DC converters. In the cases considered in this paper, by changing the core material, it was possible to achieve up to a 40% change in the value of watt-hour efficiency for the buck converter and the boost converter. It is worth noting that, for each of the considered ferromagnetic materials, there exists a range of converter input voltage, load resistance, and frequency, in which the watt-hour efficiency of the converter containing the inductor with the core made of this material was higher than for inductors with cores made of other materials.

The results of investigations presented in this paper showed that the watt-hour efficiency of buck and boost converters can strongly depend on losses in the inductor cores. The observed influence of core material on the watt-hour efficiency of DC–DC converters can be stronger than the influence of power losses in semiconductor devices. The results of computations presented in this paper were based on very simple models of phenomena occurring in the considered converters, but they allowed isolating only one mechanism of losses in the investigated converters, as well as the examination of its influence on parameters of the considered circuits. The simple model of DC–DC converter...
characteristics used during computations showed that losses in the inductor core can visibly limit the watt-hour efficiency of buck and boost converters. Of course, the obtained results of investigations showed only the direction of changes in the watt-hour efficiency of these converters while changing selected factors. In order to perform an accurate analysis of these converters, the accurate models of all the converter components should be used.

The results of the performed analyses can be useful for designers of switch mode power supplies allowing a more accurate estimation of the watt-hour efficiency of these circuits and proper selection of the material used for the inductor core. They can also be used to illustrate the influence of selected factors on the watt-hour efficiency of DC–DC converters.

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**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>(B)</td>
<td>magnetic flux density</td>
</tr>
<tr>
<td>(B_m)</td>
<td>amplitude of magnetic flux density</td>
</tr>
<tr>
<td>(d)</td>
<td>duty cycle of the signal controlling DC–DC converters</td>
</tr>
<tr>
<td>(f)</td>
<td>frequency</td>
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<tr>
<td>(I_0)</td>
<td>average value of the converter output current</td>
</tr>
<tr>
<td>(L)</td>
<td>inductance of the inductor</td>
</tr>
<tr>
<td>(P_R)</td>
<td>power losses in the inductor core</td>
</tr>
<tr>
<td>(P_V)</td>
<td>power losses density per unit of volume</td>
</tr>
<tr>
<td>(P_W)</td>
<td>power losses in the winding</td>
</tr>
<tr>
<td>(R_0)</td>
<td>converter load resistance</td>
</tr>
<tr>
<td>(S_{Fe})</td>
<td>cross-section of the core</td>
</tr>
<tr>
<td>(T)</td>
<td>period of the signal controlling DC–DC converters</td>
</tr>
<tr>
<td>(T_R)</td>
<td>core temperature</td>
</tr>
<tr>
<td>(V_e)</td>
<td>volume of the core</td>
</tr>
<tr>
<td>(V_{in})</td>
<td>converter input voltage</td>
</tr>
<tr>
<td>(V_{out})</td>
<td>converter output voltage</td>
</tr>
<tr>
<td>(z)</td>
<td>number of turns of the inductor</td>
</tr>
<tr>
<td>(\Delta I_L)</td>
<td>peak-to-peak value of inductor current</td>
</tr>
<tr>
<td>(\eta)</td>
<td>watt-hour efficiency of the tested DC–DC converter</td>
</tr>
</tbody>
</table>

**References**


17. Yue, S.; Yang, Q.; Li, Y.; Zhang, C. Core loss calculation for magnetic materials employed in SMPS under rectangular voltage excitations. AIP Adv. 2018, 8, 056121. [CrossRef]


23. Steinmetz, C.P. On the law of hysteresis. AIEE Trans. 1892, 9, 3–64. [CrossRef]


28. Parchomiuk, M. Badanie przekształtnika DC-DC z izolacją transformatorową przeznaczonego do zasilania potrzeb własnych pojazdów trakcyjnych. IAPGOS 2014, 4, 113–116. [CrossRef]


32. F867—Material Characteristics. Available online: [http://sklep.remagas.pl/images/W%C5%82a%C5%9Bciowa%C5%82u_F-867.pdf](http://sklep.remagas.pl/images/W%C5%82a%C5%9Bciowa%C5%82u_F-867.pdf) (accessed on 16 May 2019).

