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MAGNETICS ELEMENTS FOR POWER ELECTRONIC CONVERTERS

Magnetic devices are an important part of the power electronics converter. The realization of the magnetic elements must be connected to the converter design. Projects of the power electronics devices include models and converter design, models and magnetic elements design. The described design of magnetic parts for power electronics converters is the topic of this article. In this paper, the basic theory is reviewed, including magnetic circuits equations and inductor modelling. Power losses in winding conductors are also important. This can lead to copper losses significantly in excess of the value predicted by the dc winding resistance. The "skin effect" and the "proximity effect" are most pronounced in high-current conductors of multilayer windings, particularly in high-frequency converters. This article explains and provides practical methods to compute these losses. The aim of this paper is calculation of magnetic devices, their losses, and the design of magnetic devices for power electronics converters.

Keywords: inductor design, magnetic elements, copper losses

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1. Introduction

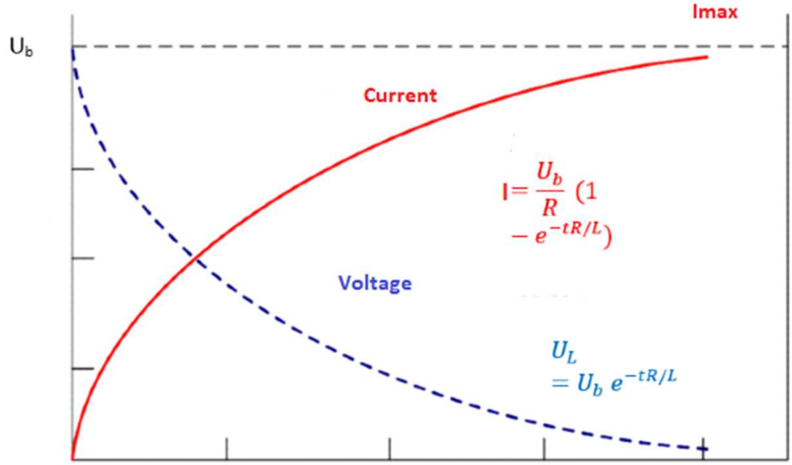
The induction coil is an element that stores energy inside the core in the form of a magnetic field. Change in the current flowing through the windings, generates an electromotive force. The induction coil consists of a core and insulated coils of conductor wrapped around it. The core of the coil may be made out of magnetic materials or alternatively as air core coil. The coil is not a complicated element, however, the selection of the coil for the power electronic system requires careful and precise calculations [1]. That is why, inductors and transformers play a crucial role in modern power electronics circuits. Incorrect calculations can lead to exceeding the allowed temperature or voltage, and as a result, damage this element [2].

Two predominant types of power loss are considered in power electronic circuit coil applications. The first is the loss occurring at the series resistance, that is, at the resistance of the winding wire. This power loss should be given special consideration when the current flowing through the coil is high. It is most frequently encountered in power supplies and power circuits. This type of loss causes heating of the coil and, consequently, of the entire device. It is also the most common cause of damage, as high temperatures can damage the insulation and cause a short circuit of the coil. The second type of power loss is that that occurs in the core. These occur because of unevenness of the core, the occurrence of eddy currents, and changes in the position of the magnetic domains. These losses can be encountered in high-frequency circuits [3].

1.1. The inductor – basic parameters

The basic parameters of a coil are its inductance and resonant frequency. Inductance is the ability of a coil to store energy in the form of a magnetic field induced by the flow of current (Fig. 1). The inductance L is measured in [H] and expressed as the ratio (1) of the instantaneous voltage u to the change in current over time di/dt [4-5].

$$u_L = -L\frac{di}{dt} \tag{1}$$



Rys. 1. Wykresy spadku prądu i napięcia na zaciskach cewki indukcyjnej
Fig. 1. Diagrams of current and voltage drop at the terminals of an induction coil

1.2. Inductor core losses

In traditional core loss calculation model, the core is considered as a whole. The core losses (iron) consists of two parts: hysteresis and eddy current losses [6]. The hysteresis losses are proportional to $B\text{–}H$ the loop area and excitation frequency f. They can be calculated by Eq. (2):

$$P_h = k_h f B^2 \tag{2}$$

Whereas, eddy-current losses are proportional to $(f{\cdot}B)^2$ as in Eq. (3). They play an increasingly significant role once the frequency rises to tens and hundreds of kilohertz.

$$P_e = k_e (fB)^2 \tag{3}$$

Where, k_h and k_e are waveform coefficients of excitation voltage, f is the operating frequency of the core, and B is the magnitude of flux density.

The coefficients k_h and k_e depended on the used materials have been characterized and provided by manufacturers of core [7].

After the winding is excited, the magnetic flux density of the core and core loss can be calculated.

1.3. Inductor winding losses

Inductors made out of common, parallel windings are considered. This model can be used for inductors wound on round magnetic cores. The time-average real power loss P_{wN} in the n-th turns was shown in (4):

$$P_{wN} = R_{wN} * {I_{rms}}^2 = (R_{skinN} + R_{proxN}) * {I_{rms}}^2 \tag{4}$$

where $R_{skinN} = R_{skin}$ is the resistance of each turn due to the skin and R_{proxN} is the resistance of the n-th turn due to the proximity effect and significant increases from the innermost layer to the outermost layer.

2. The coil selection

This part of the paper provides a possible approach to the design of coils for low-power electronics applications. Many parameters are involved in such a design flow, therefore, different approaches are possible according to which one is considered the most relevant one rom presented perspective, the selection of the coil is carried out according to the recommendations of the manufacturer of the magnetic cores.

2.1. Coil parameters mathematical calculation

The first selection step is to determine the $L*I^2$ parameter according to equation (5), binding the inductance and the current that will flow through the coil.

$$L * I^2 = L_B * {I_{wejB}}^2 = 19.3 * 10^{-6} * 61.2^2 = 72.3\ mH * A^2 \tag{5}$$

Based on this parameter a toroidal core from the characteristics shown in Figure 1 a core (with part number 77686 [8]). The calculation of the number of turns of the coil was made by (6):

$$N = \sqrt{\frac{L}{A_L}}, \tag{6}$$

where:
L - inductance of the coil,
A_L - parameter reported in the core data sheet, $\frac{mH}{T^2}$.

$$A_L = 30\frac{mH}{T^2}. \tag{7}$$

$$N = \sqrt{\frac{L_B}{A_L}} = \sqrt{\frac{19.3*10^{-6}}{30*10^{-3}}} = 25.4 \cong 26. \tag{8}$$

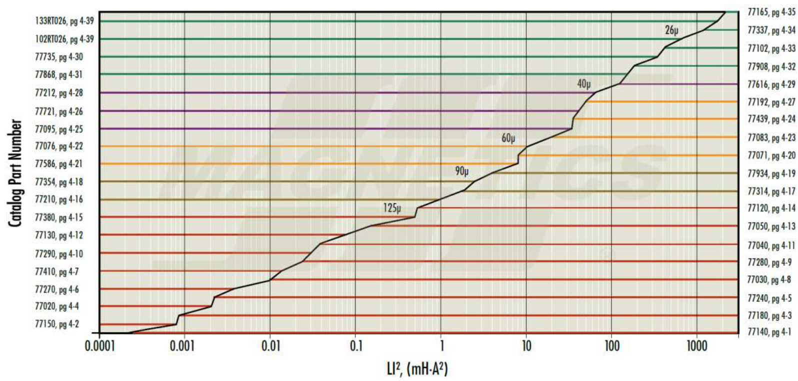
Subsequently, we determine by how much the magnetic permeability will decrease for the calculated magnetic intensity of the core H_L, (Fig. 2). Magnetic permeability of the selected core is given in (9):

$$H_L = \frac{N*I}{L_e}, \tag{9}$$

where:
N – number of turns,
I – coil current,
L_e – path of magnetic flux. The value is read from the data sheet.

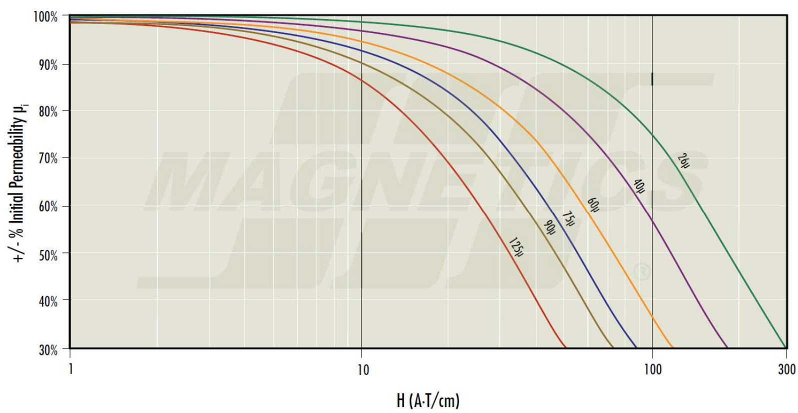
Calculation of the magnetic intensity for the determined magnetic flux path $L_e = 19.6\ cm$

$$H_L = \frac{N*I_{wyjP}}{L_e} = \frac{141*5.84}{12.7} = 81.1\ \frac{A*T}{cm} \tag{10}$$



Rys. 1. Charakterystyka doboru rdzenia, materiał Kool Mµ [8]

Fig. 1. Core selection characteristics, material Kool Mµ [8]



Rys. 2. Charakterystyka przenikalności magnetycznej [8]

Fig. 2. Characteristics of magnetic permeability [8]

Kool Mμ material's low loss and relatively high saturation level. Magnetic permeability of the selected core given in (11):

$$\mu = 26\ \frac{H}{m} \tag{11}$$

The reduced permeability of the core will be approximately 80%, which is associated with an increase in the number of turns.

$$N_L = \frac{N}{0.8} = \frac{26}{0.8} = 33 \tag{12}$$

Estimated current density flowing through the coil winding:

$$j = 3\ \frac{A}{mm^2} \tag{13}$$

Calculation of the cable cross-sectional area:

$$S_{cu} = \frac{I_{wejB}}{j} = \frac{61.2}{3} = 20.4\ mm^2 \tag{14}$$

A conductor with this cross-sectional area is relatively thick, so a spliced face of thinner conductors will be used AWG 14 [8].

$$S_{cuL} = 2.082\ mm^2 \tag{15}$$

Determination of the number of wires:

$$N_W = \frac{S_{cu}}{S_{cuL}} = \frac{20.4}{2.082} = 9.79 \cong 10 \tag{16}$$

Calculation of the conductive surface of the conductor front:

$$S_L = 10 * S_{cuL} = 10 * 2.082 = 20.82\ mm^2 \tag{17}$$

Cross-sectional area of a single-face cable with insulation [8]:

$$S_{cuL\ iz} = 2.295\ mm^2 \tag{18}$$

The cross-sectional area of winding was calculated in Eq. (19):

$$S_{uzw} = 10 * N_L * S_{cuL\ iz} = 10 * 33 * 2.295 = 757.4\ mm^2 \tag{19}$$

Calculation of the fill rate of the toroid window:

$$W_A = 1820\ mm^2 \tag{20}$$

$$\frac{S_{uzw}}{W_A} = 0.416 \tag{21}$$

For 45% core window fill, the length of one coil is:

$$L_Z = 86.7\ mm \tag{22}$$

The length of one wire will be:

$$L_P = N_L * L_Z = 33 * 86.7 = 286\ cm \tag{23}$$

The selection of parameters of an inductor with an appropriate inductance value, number of turns, etc., intended for the cooperation of the power electronic converter was shown step by step.

3. Inductor loss calculation

As power supply output current requirements continue to increase, it is important to consider inductor power losses and their impact on overall power supply efficiency. To reduce these losses, it is necessary to understand where they come from. There are several inherent losses associated with inductors.

3.1. Winding loss calculation

To select losses, the coil winding resistance should be calculated as necessary. For the calculated length of the coil winding (23), the cable resistance (24) was read from catalogue data [8]:

$$R_0 = 82.8\ \frac{\mu\Omega}{cm} \tag{24}$$

Thus, the resistance of a single coil is:

$$R = R_0 * L_P = 82.8 * 10^{-6} * 286 = 0.024\ \Omega \tag{25}$$

Coil resistance, meanwhile (26):

$$R_L = \frac{1}{\frac{10}{R}} = \frac{1}{\frac{10}{0.024}} = 2.37\ m\Omega \tag{26}$$

The power loss of a winding is defined in (27):

$$\Delta P_{cu} = I^2 * R_L = 61.2^2 * 2.37 * 10^{-3} = 8.86\ W \tag{27}$$

3.2. Core loss calculation

The first step in calculating the power loss in the core is to determine the magnetic induction of the core knowing the magnetising force. This is done using the characteristics provided by the manufacturer (Fig. 3). For the calculated value of H_L according to relation (9) and the assumed value of magnetic induction B= 0.25 T, the power loss was read from the characteristic curve in Figure 4.

$$\Delta P \cong 5000\ \frac{mW}{cm^3} \tag{28}$$

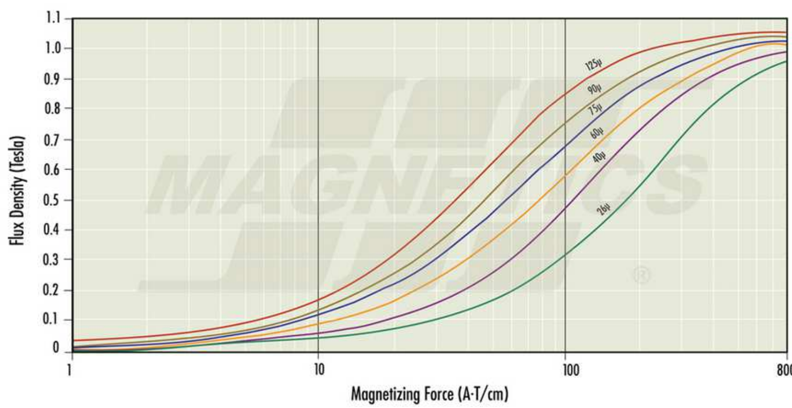
The volume of the core is $V\_e = 34.5\ cm^3$.

Hence the power losses are as follows:

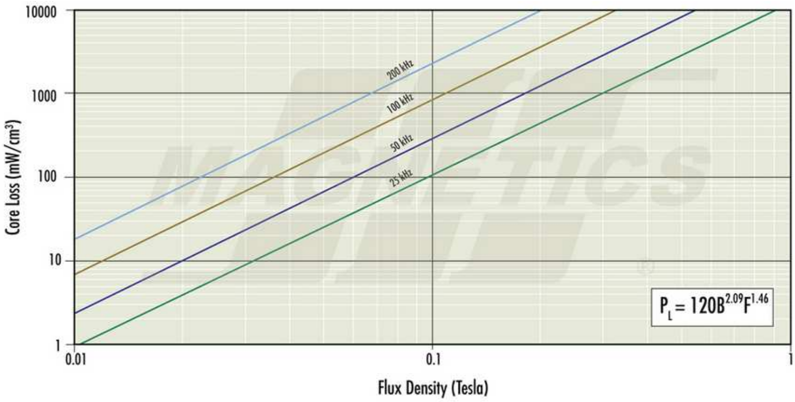
$$\Delta P_{CL} = \Delta P * V_e = 5 * 34.5 = 172.5\ W \tag{29}$$

The total coil losses are:

$$\Delta P_{LB} = \Delta P_{cu} + \Delta P_{CL} = 8.86 + 172.5 = 181.4\ W \tag{30}$$



Rys. 3. Charakterystyka indukcji magnetycznej [8]
Fig. 3. Magnetic induction characteristics [8]



Rys. 4. Charakterystyka strat mocy w rdzeniu w zależności od indukcji magnetycznej [8]
Fig. 4. Characteristics of power loss in the core as a function of magnetic induction [8]

4. Summary

It is very important to determine the power loss of the inductor; losses are limited by the maximum permissible surface temperature of coil. Thus, for most designs, this limit is 125°C. It is also the most common cause of damage, as high temperatures can damage the insulation and cause a short circuit of the coil. The predominant types of power loss are considered in coil applications. The first is the loss that occurs at the resistance of the winding wire, called "Cu losses". This power loss should be given special consideration when the current flowing through the coil is high. It is most often encountered in power supplies and power circuits. This type of loss causes heating of the coil and, consequently, of the entire device.

The second type of power loss is that occurs in the core. These occur because of unevenness of the core, the occurrence of eddy currents, and changes in the position of the magnetic domains. These losses are prevalent when the current flowing through the coil is low. They can be encountered in high-frequency circuits, digital signal separators and others. It leads not so much to coil damage as to signal level loss problems in sensitive circuits.

The aim of the paper was an explanation of the calculation of magnetic devices, their losses, and the design of magnetic devices for power electronics converters.

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ELEMENTY MAGNETYCZNE DLA PRZEKSZTAŁTNIKÓW ENERGOELEKTRONICZNYCH

Streszczenie

Urządzenia magnetyczne są ważnym elementem każdego przekształtnika energoelektronicznego. Zawsze realizacja elementów magnetycznych musi być związana z projektem przekształtnika. Projekty urządzeń energoelektronicznych obejmują modele i projekty przekształtników, a także modele i projekty elementów magnetycznych. Opisane projektowanie elementów magnetycznych dla przekształtników energoelektronicznych jest tematem tego artykułu. W niniejszym artykule dokonano przeglądu podstawowej teorii, w tym równania obwodów magnetycznych i modelowania induktora. Istotne są również straty mocy w przewodach uzwojenia. Może to prowadzić do strat w miedzi znacznie przekraczających wartość przewidywaną przez rezystancję uzwojenia prądu stałego. "Efekt naskórkowości" jest najbardziej wyraźny w wysokoprądowych przewodach uzwojeń wielowarstwowych, szczególnie w przetwornicach wysokiej częstotliwości. Niniejszy artykuł wyjaśnia i podaje praktyczne metody obliczania tych strat. Celem artykułu są obliczenia urządzeń magnetycznych, ich strat oraz projektowanie urządzeń magnetycznych dla przekształtników energoelektronicznych.

Słowa kluczowe: projektowanie cewek indukcyjnych, elementy magnetyczne, straty w miedzi

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